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Yamada et al.

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(54) **MAGNETIC RECORDING HEAD, MAGNETIC HEAD ASSEMBLY, MAGNETIC RECORDING APPARATUS, AND MAGNETIC RECORDING METHOD**

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Related U.S. Application Data

(62) Division of application No. 14/184,406, filed on Feb. 19, 2014, now Pat. No. 8,995,085, which is a division of application No. 12/591,752, filed on Nov. 30, 2009, now Pat. No. 8,767,346.

(30) **Foreign Application Priority Data**

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(51) **Int. Cl.**

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G11B 5/09 (2006.01)
G11B 5/127 (2006.01)

(52) **U.S. Cl.**

CPC ... ***G11B 5/09*** (2013.01); ***G11B 5/35*** (2013.01)

(58) **Field of Classification Search**

CPC G11B 5/35; G11B 5/09; G11B 5/1278; G11B 5/3123; G11B 5/3133; G11B 2005/001; G11B 5/17

USPC 360/123.11, 125.3, 119.03

See application file for complete search history.

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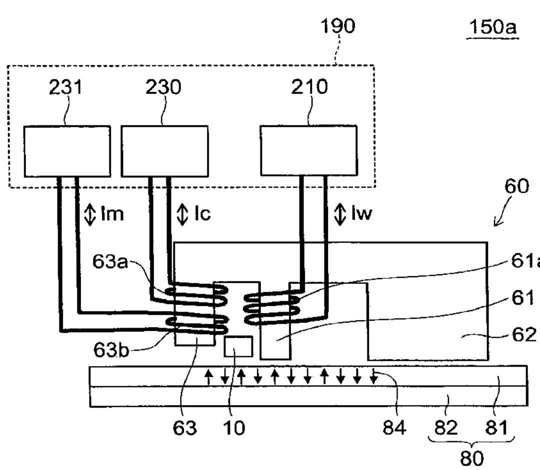
(57) **ABSTRACT**

An example magnetic recording apparatus includes a magnetic recording medium, a magnetic recording head and a signal processor. The magnetic recording head includes a first magnetic pole; a second magnetic pole; a spin torque oscillator; a first coil to magnetize the first magnetic pole; and a second coil through which a current is passed independently of the first coil. The signal processor writes and reads a signal on the magnetic recording medium by using the magnetic recording head and includes a first current circuit to supply a recording current to the first coil and a second current circuit to supply a modulating current to the second coil.

3 Claims, 32 Drawing Sheets



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Office Action mailed Sep. 18, 2013 in counterpart Japanese Application No. 2012-069974 and English-language translation of same.

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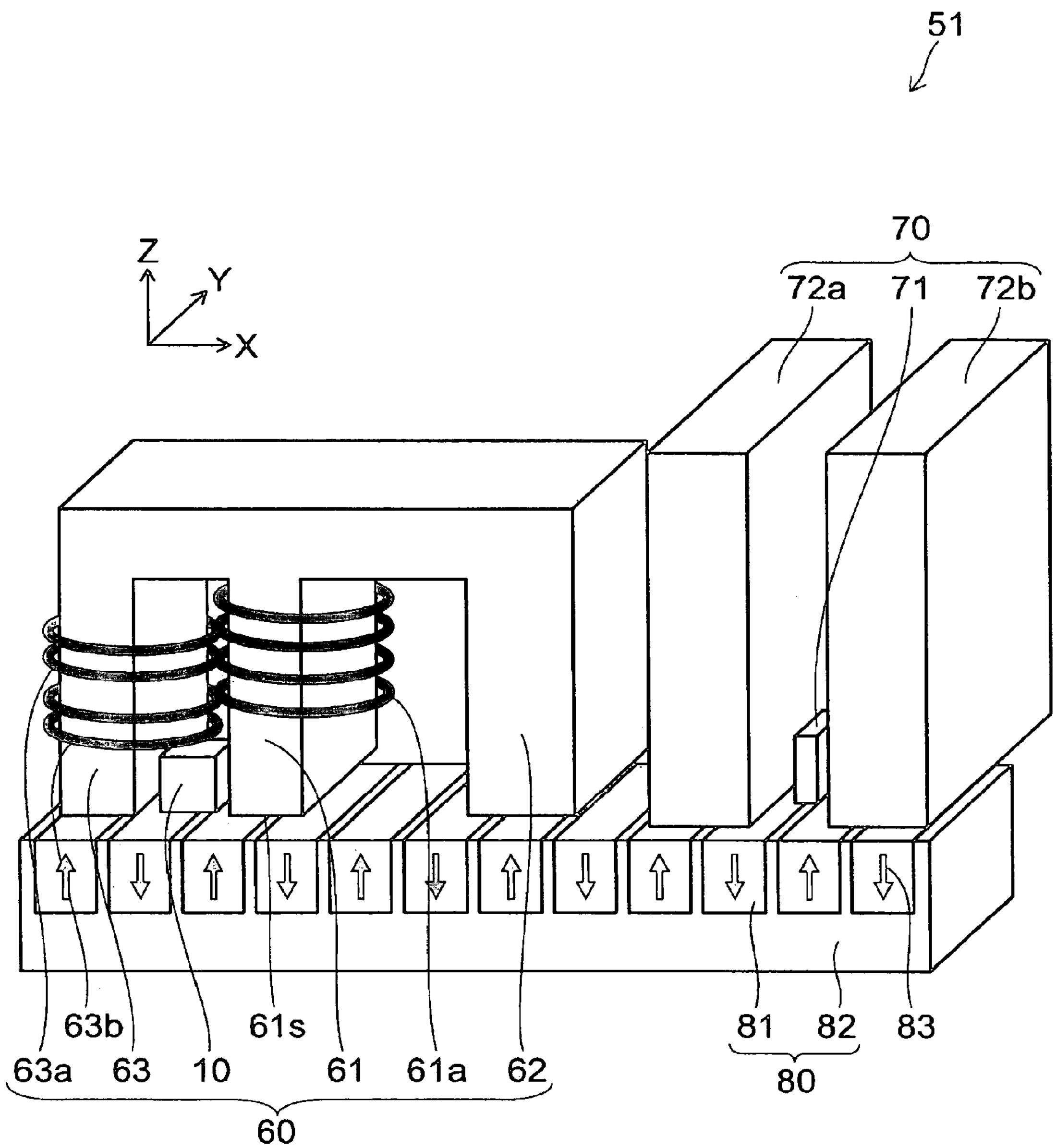


FIG. 1

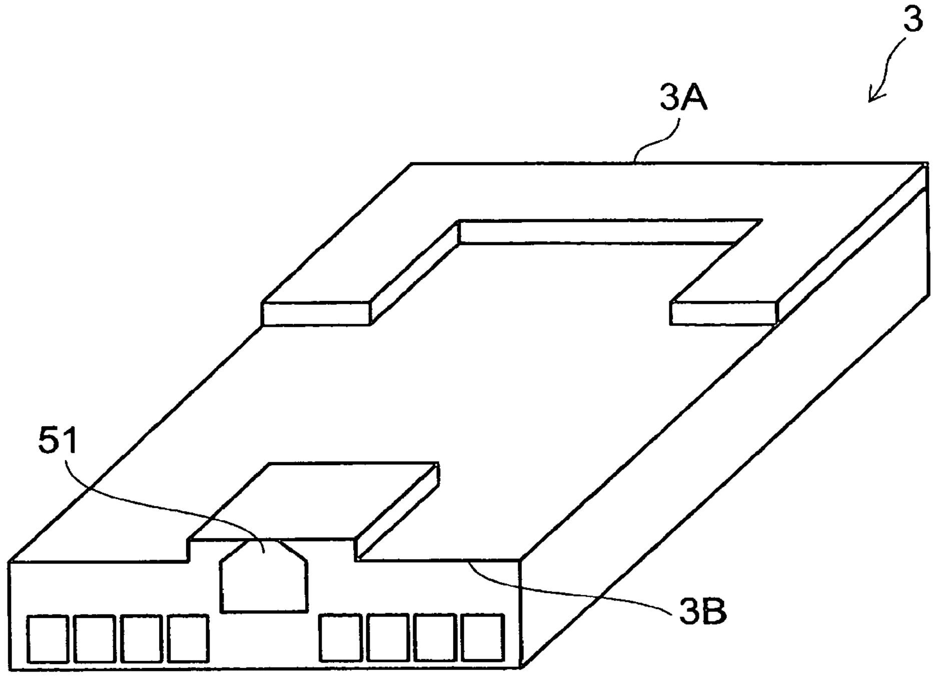


FIG. 2

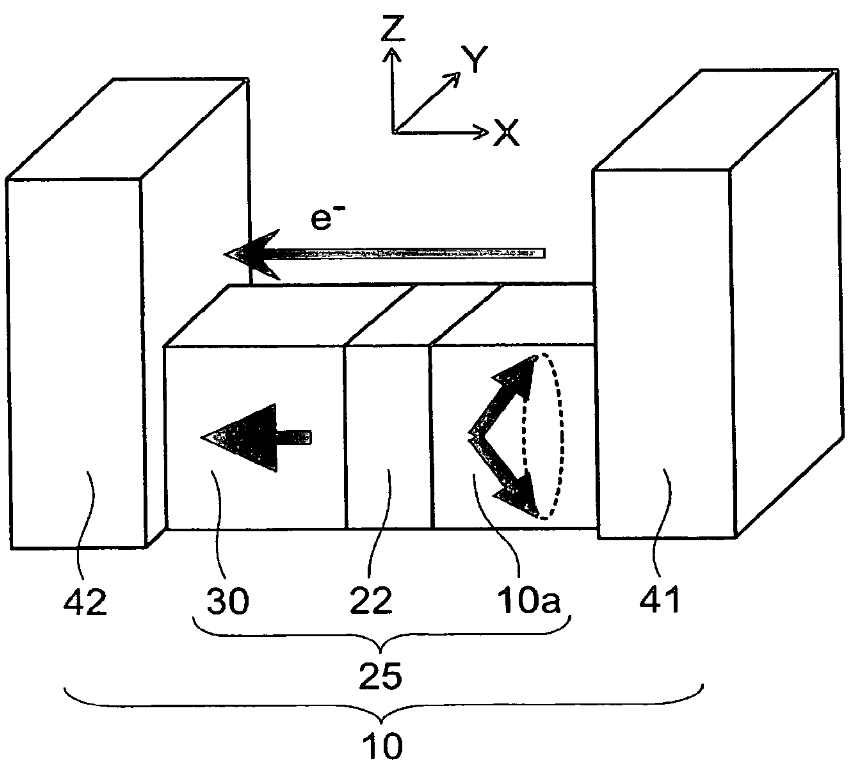


FIG. 3

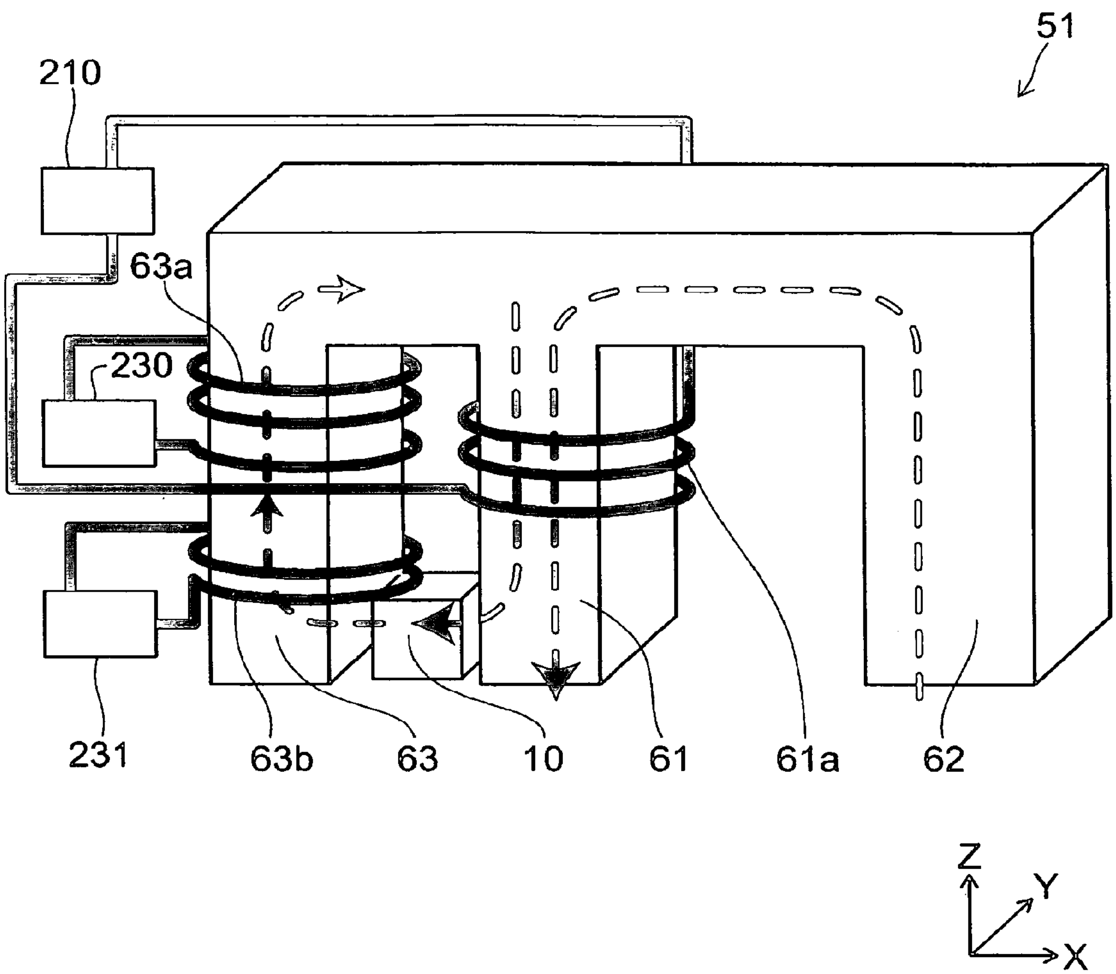


FIG. 4

FIG. 5A

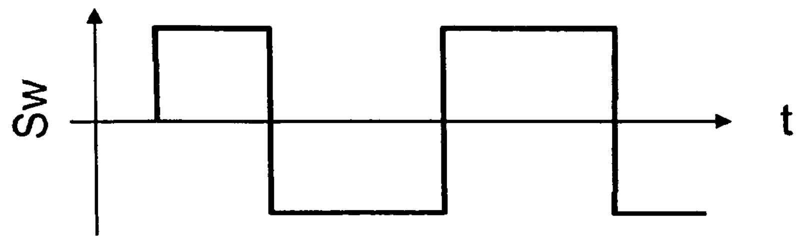


FIG. 5B

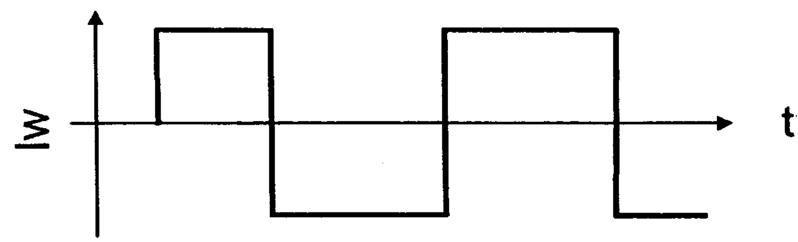


FIG. 5C

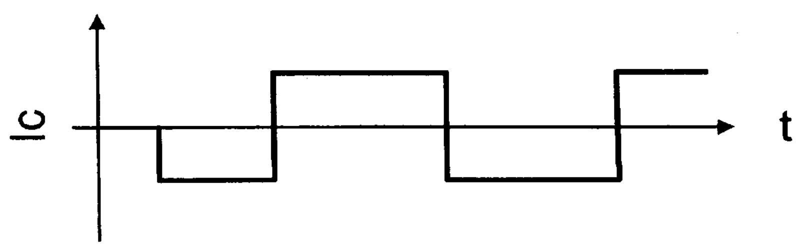


FIG. 5D

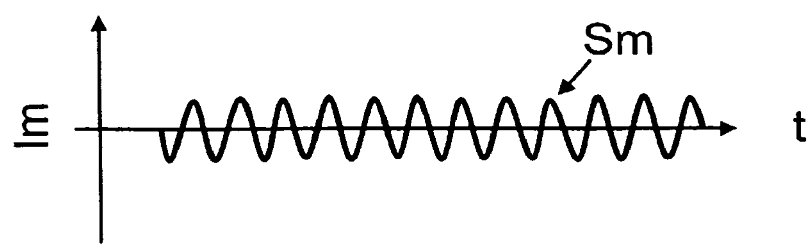


FIG. 6A

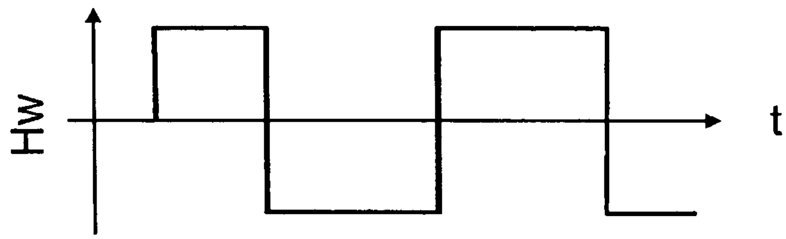


FIG. 6B

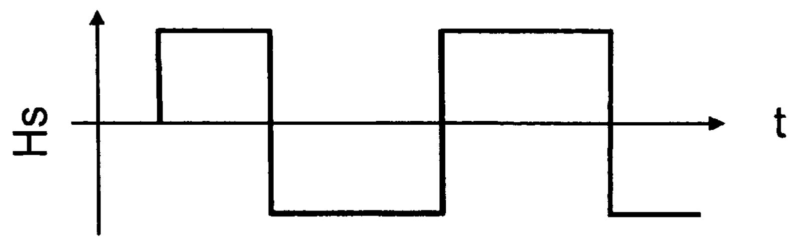


FIG. 6C

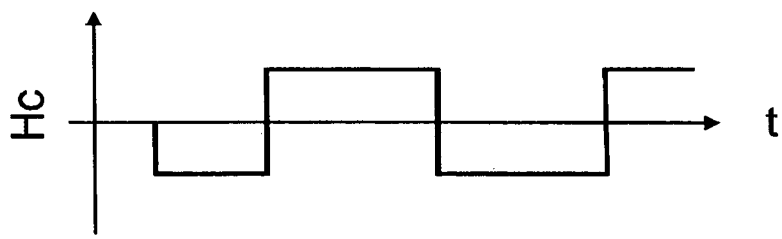


FIG. 6D

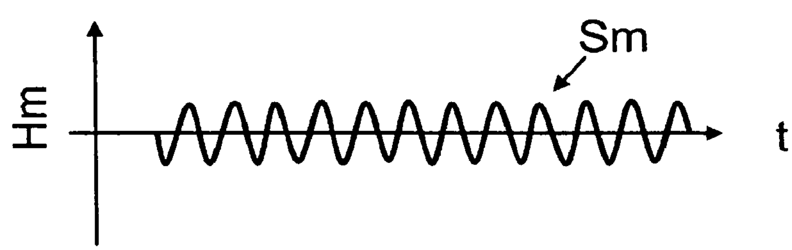
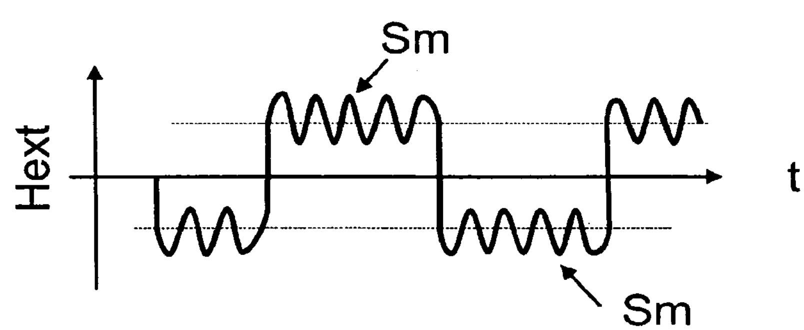
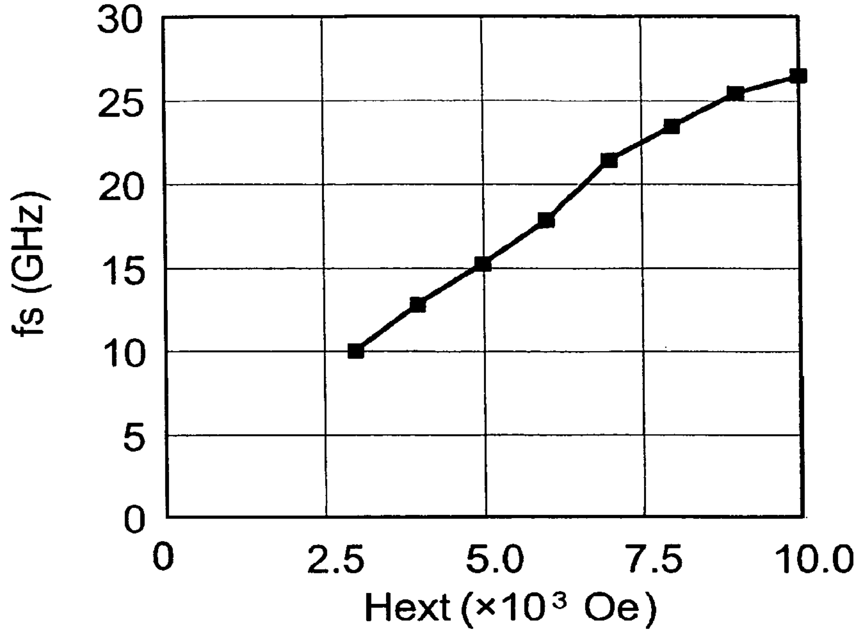


FIG. 6E

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5.0
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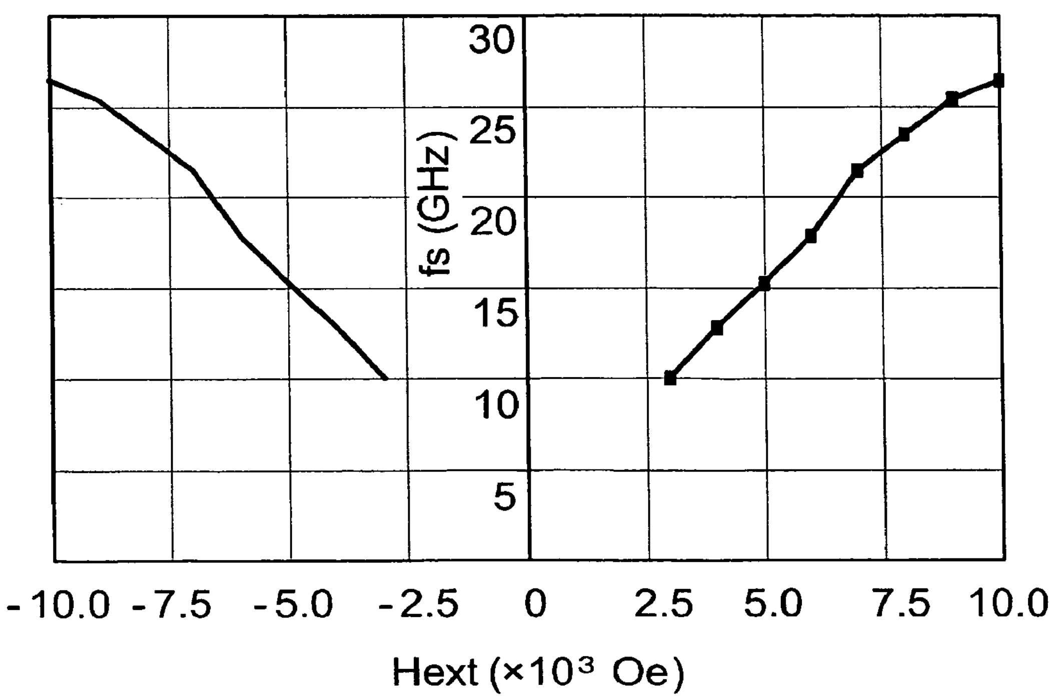
10.0
Hext (×10³ Oe)

FIG. 7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-10.0
-7.5
-5.0
-2.5
0
2.5
5.0
7.5
10.0
Hext (×10³ Oe)

FIG. 8

FIG. 9A

FIG. 9B

FIG. 9C

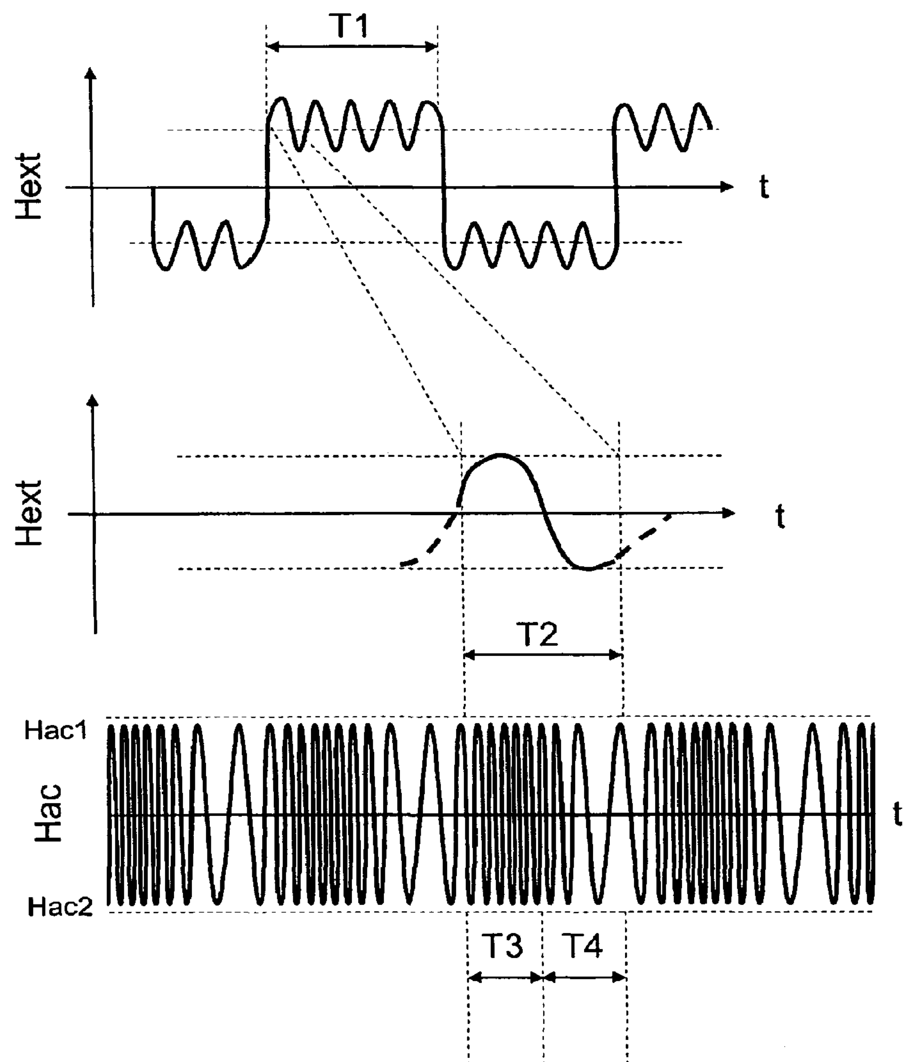


FIG. 10A

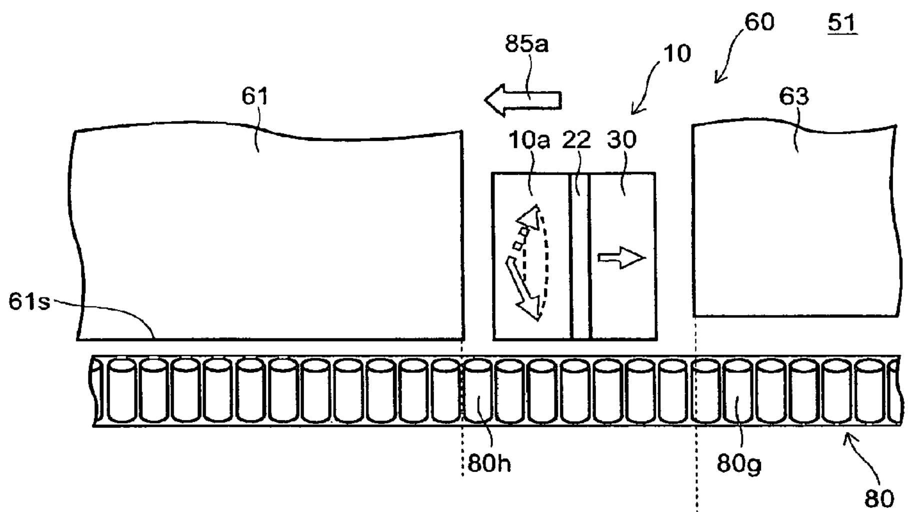
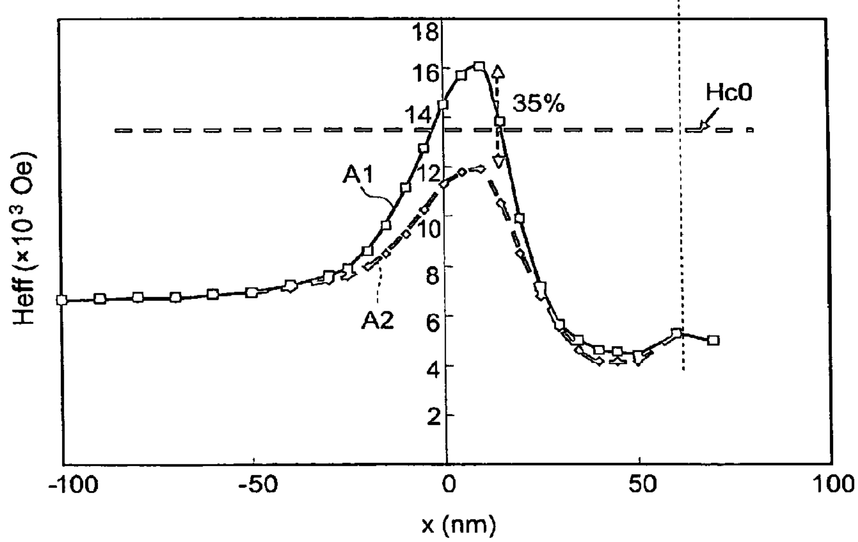


FIG. 10B



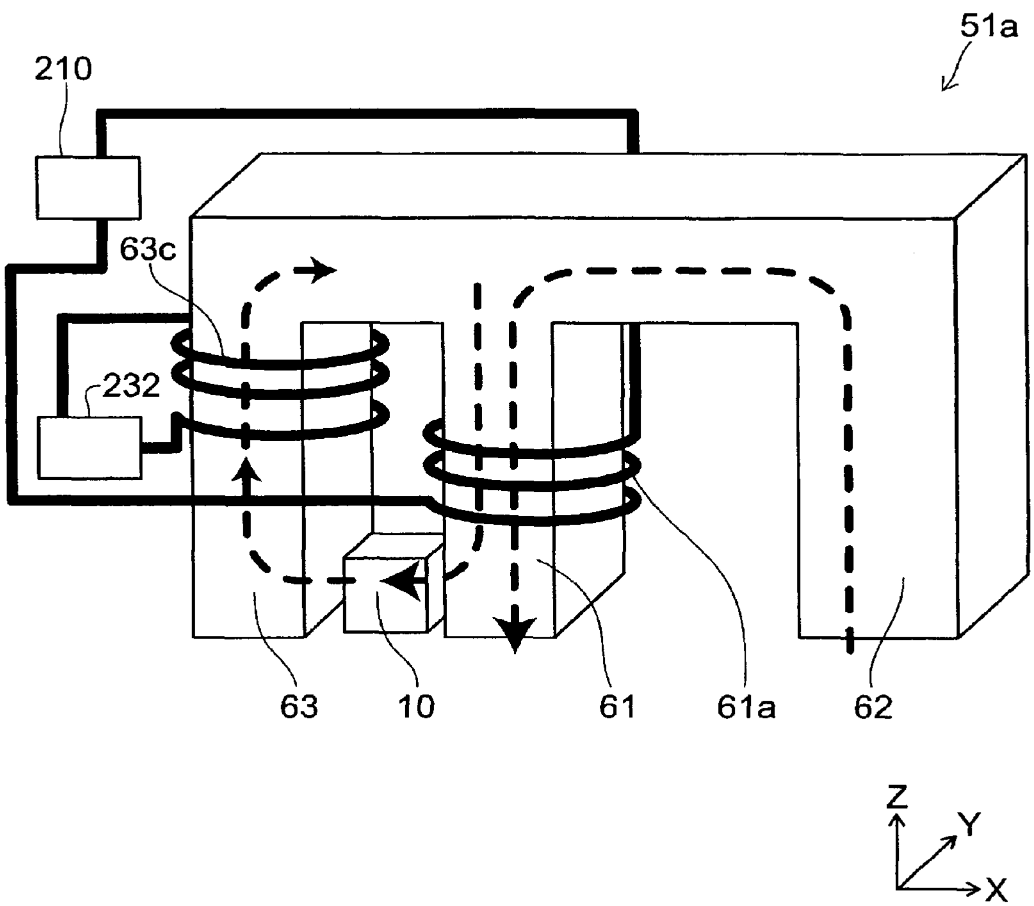


FIG. 11

FIG. 12A

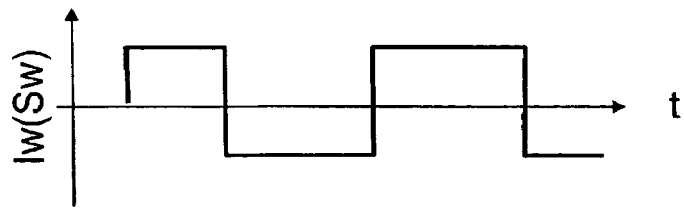


FIG. 12B

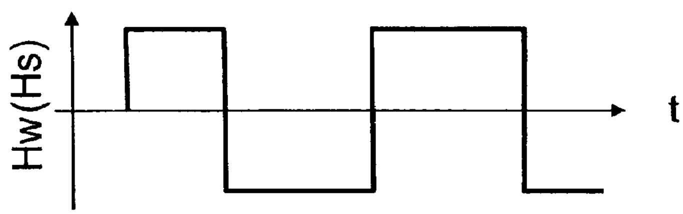


FIG. 12C

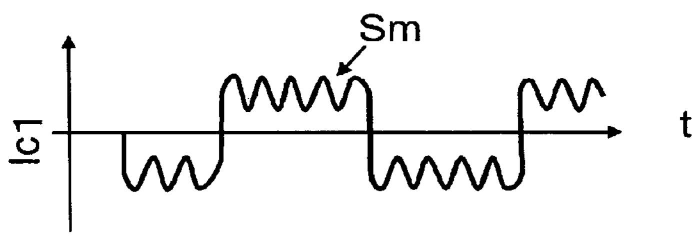


FIG. 12D

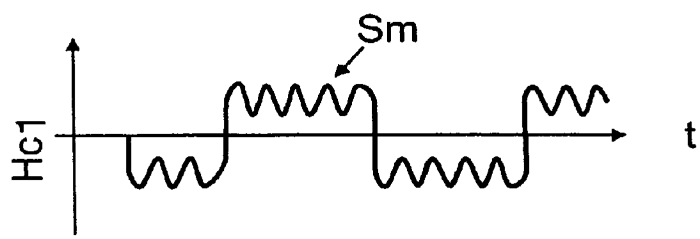
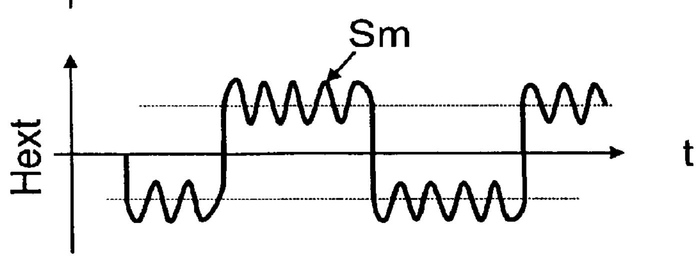


FIG. 12E



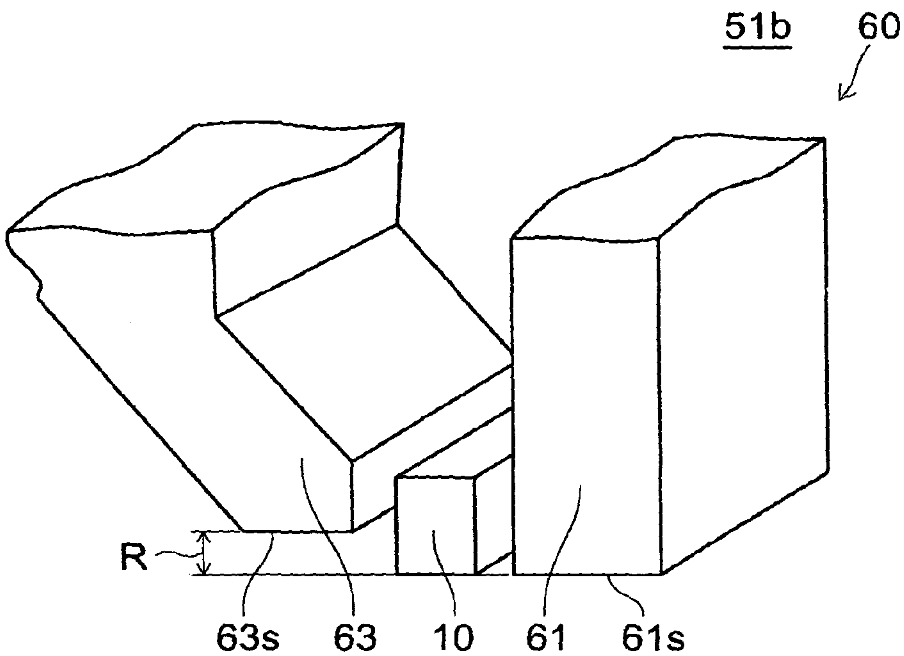


FIG. 13

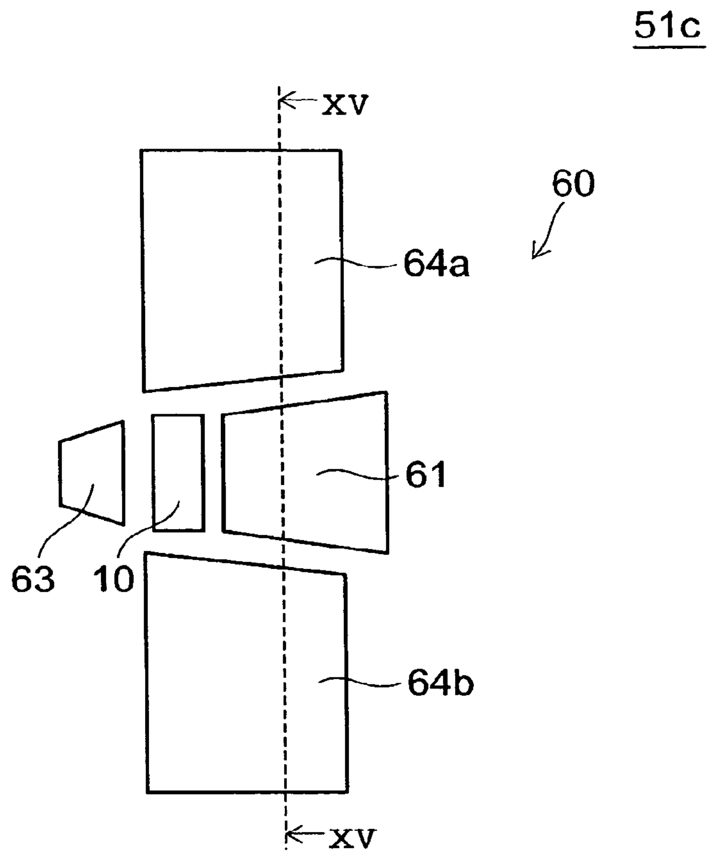


FIG. 14

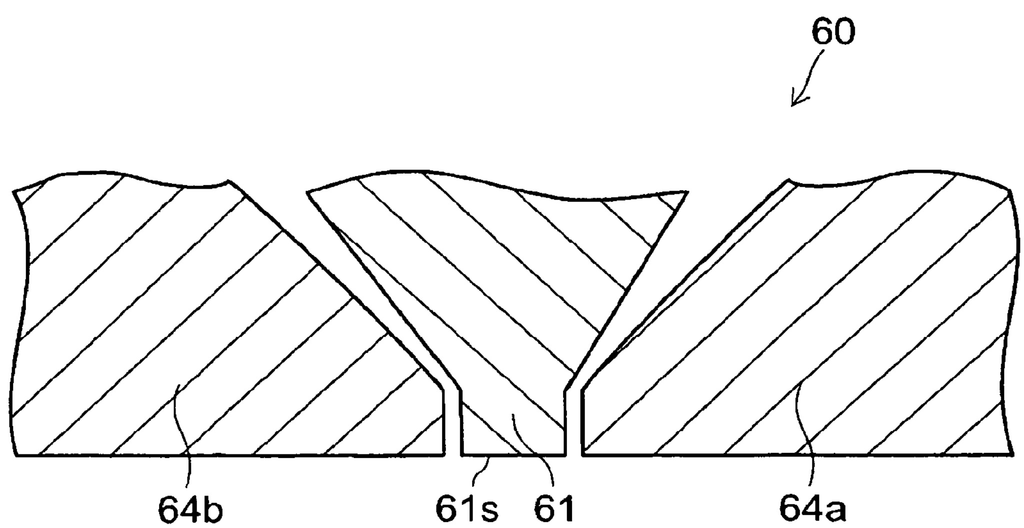


FIG. 15

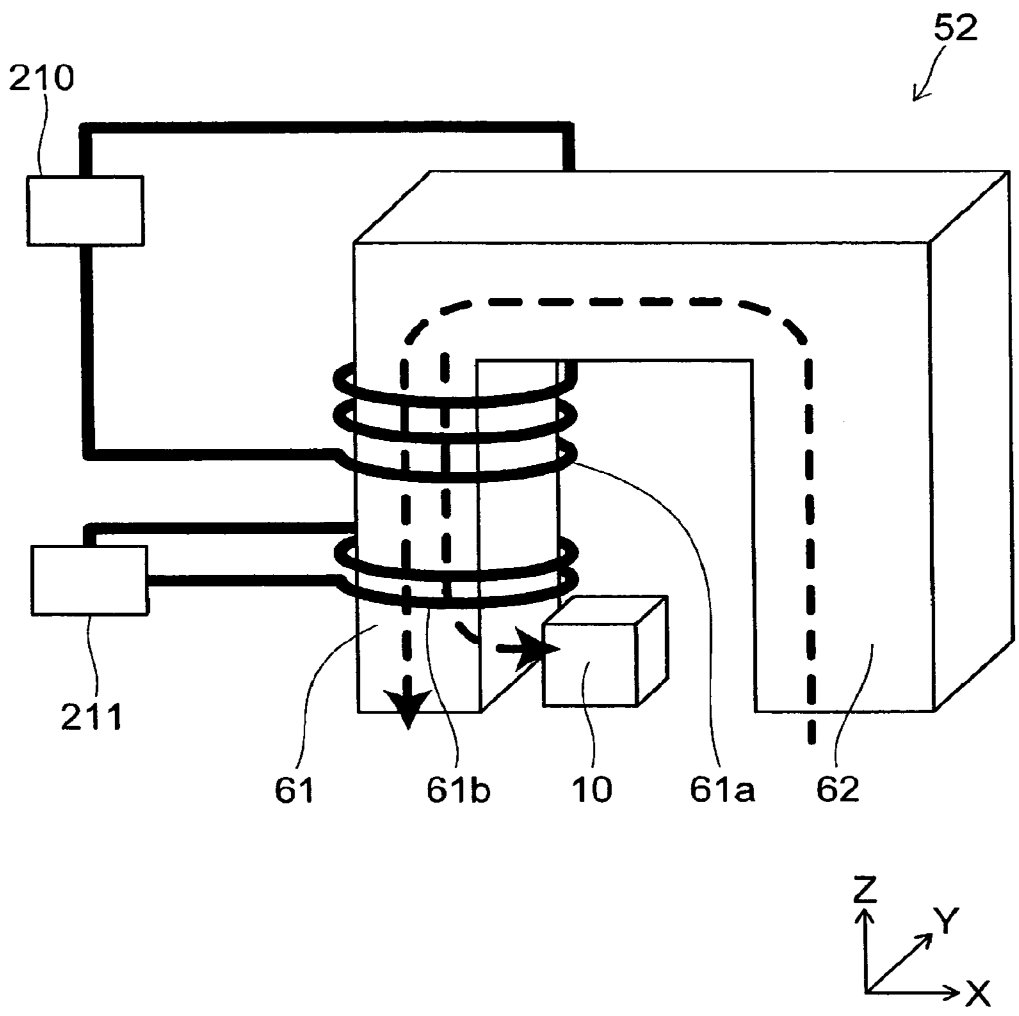


FIG. 16

FIG. 17A

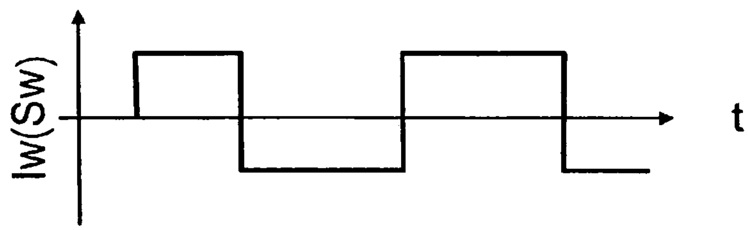


FIG. 17B

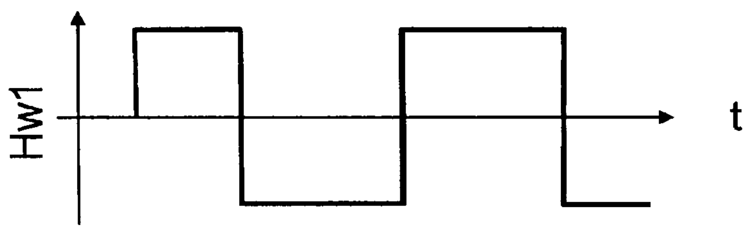


FIG. 17C

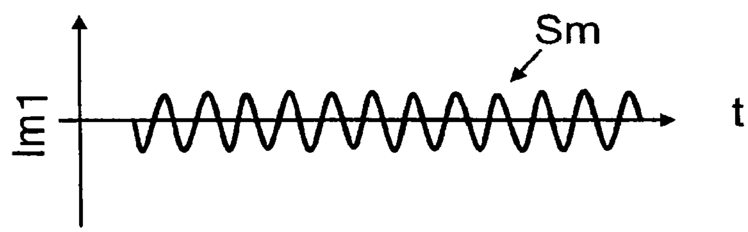


FIG. 17D

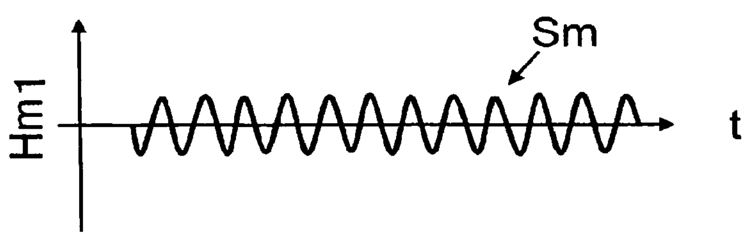
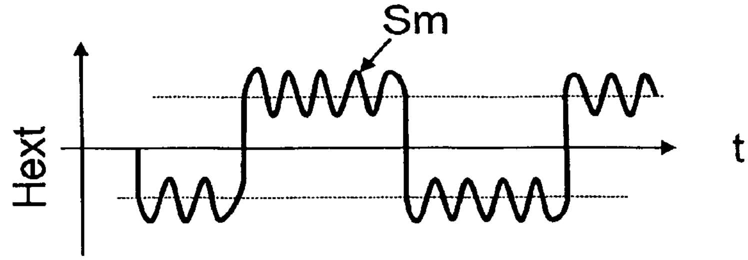


FIG. 17E



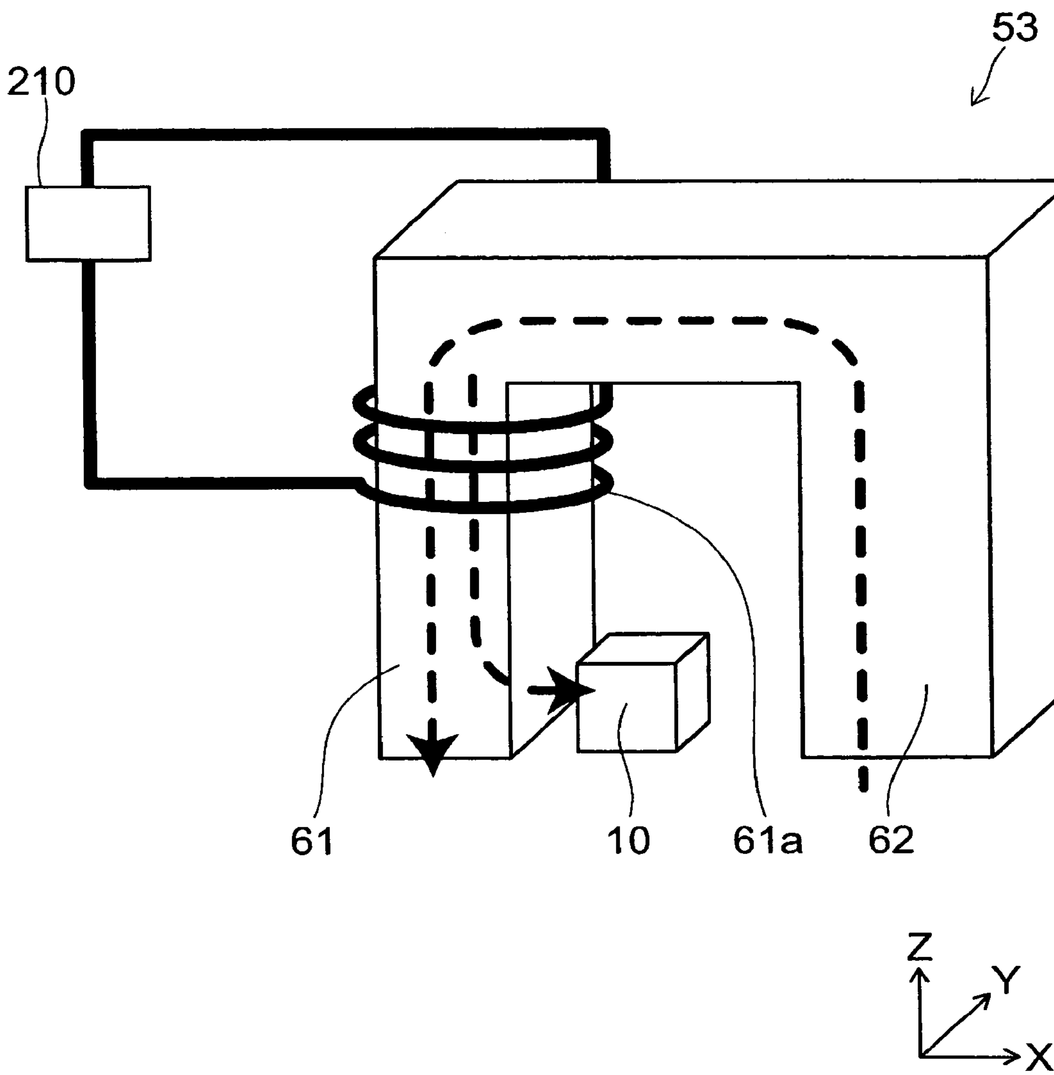


FIG. 18

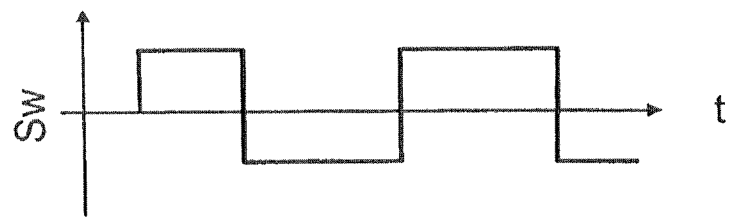


FIG. 19A

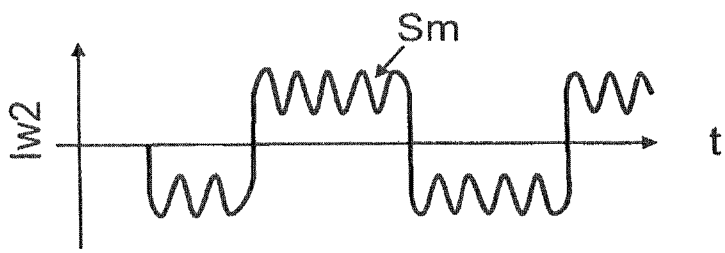


FIG. 19B

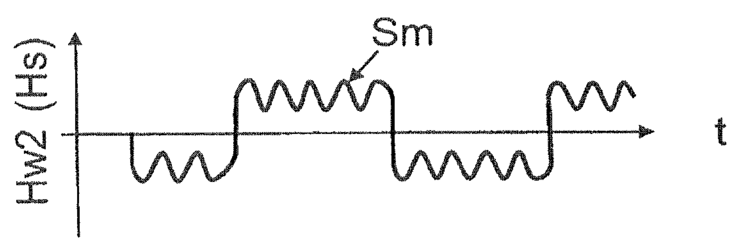


FIG. 19C

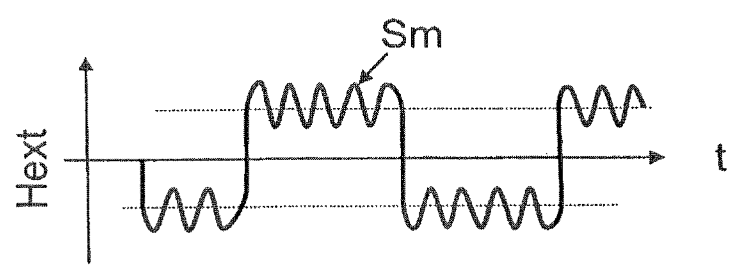


FIG. 19D

FIG. 20A

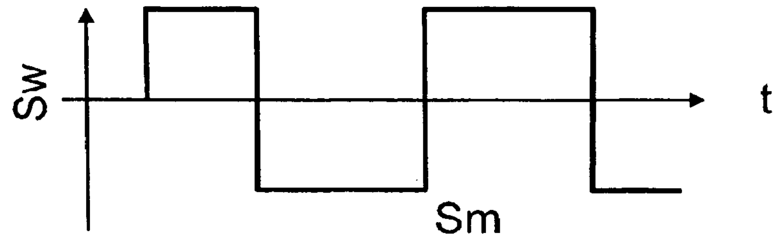


FIG. 20B

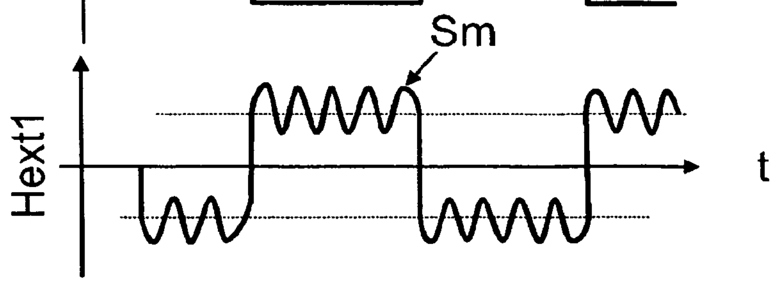


FIG. 20C

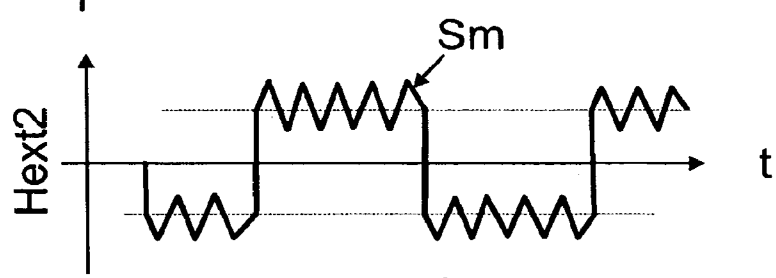


FIG. 20D

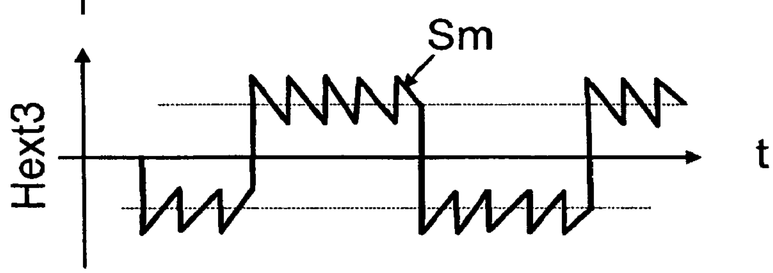


FIG. 20E

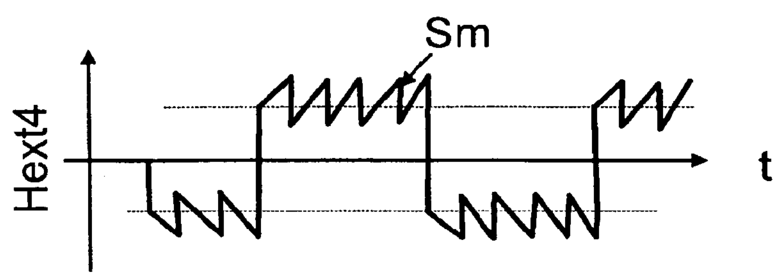


FIG. 20F

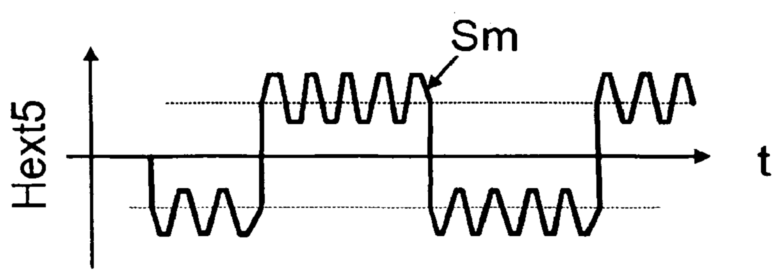


FIG. 21A

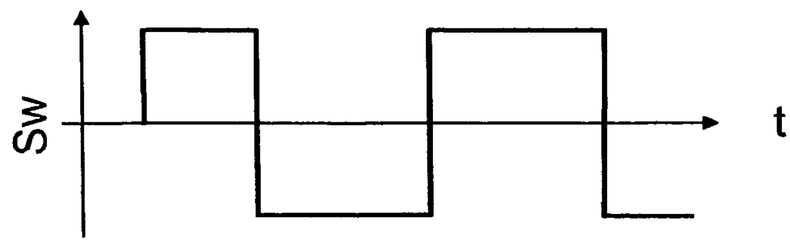


FIG. 21B

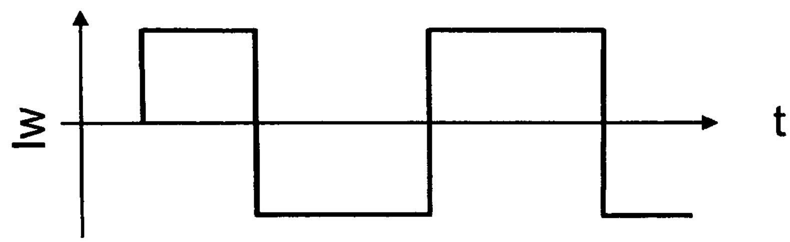


FIG. 21C

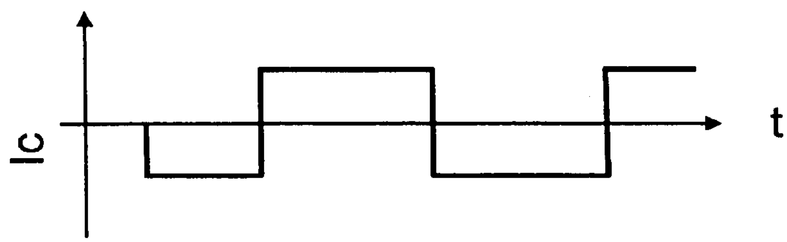


FIG. 21D

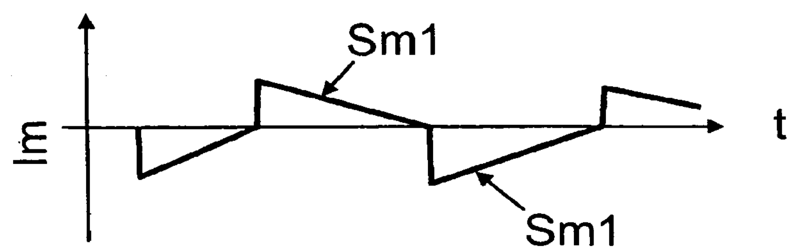


FIG. 22A

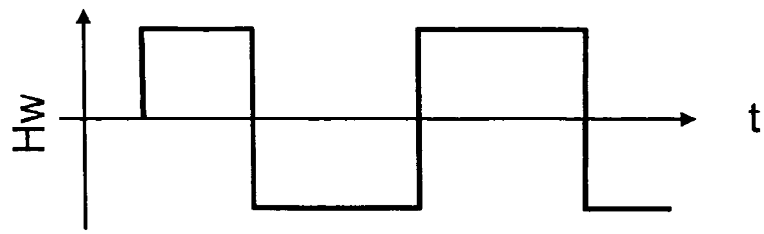


FIG. 22B

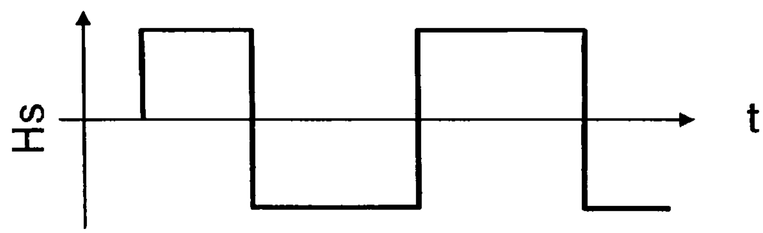


FIG. 22C

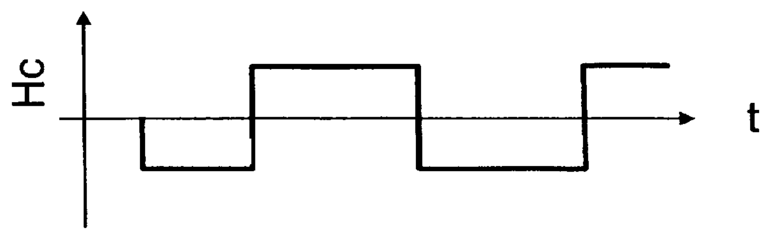


FIG. 22D

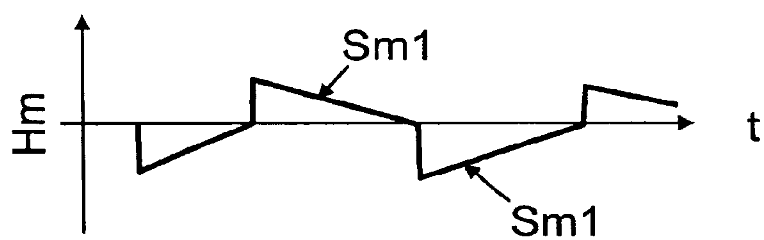
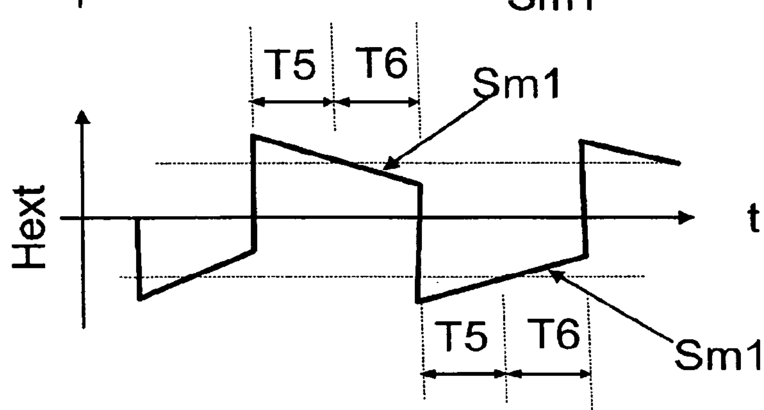


FIG. 22E



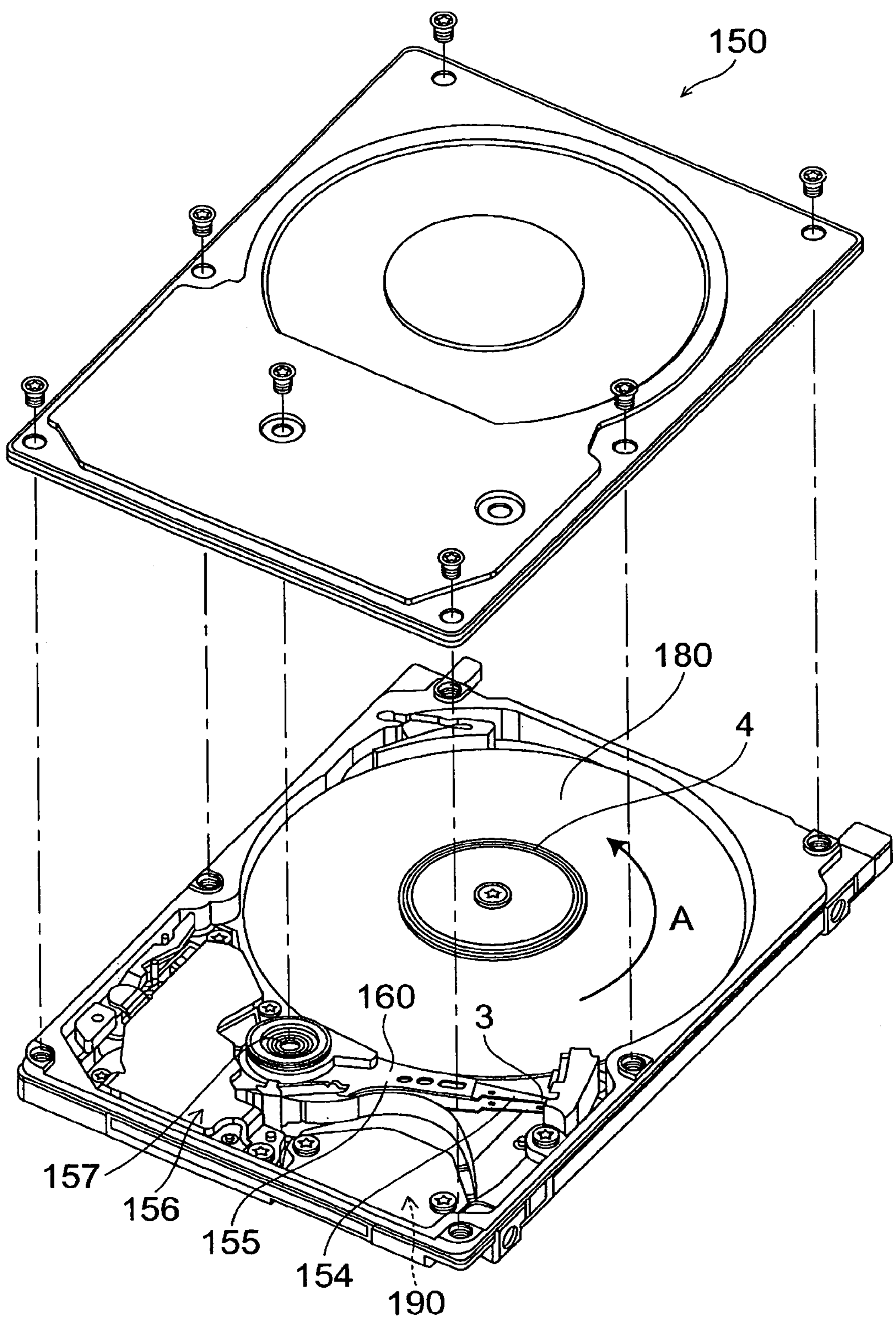


FIG. 23

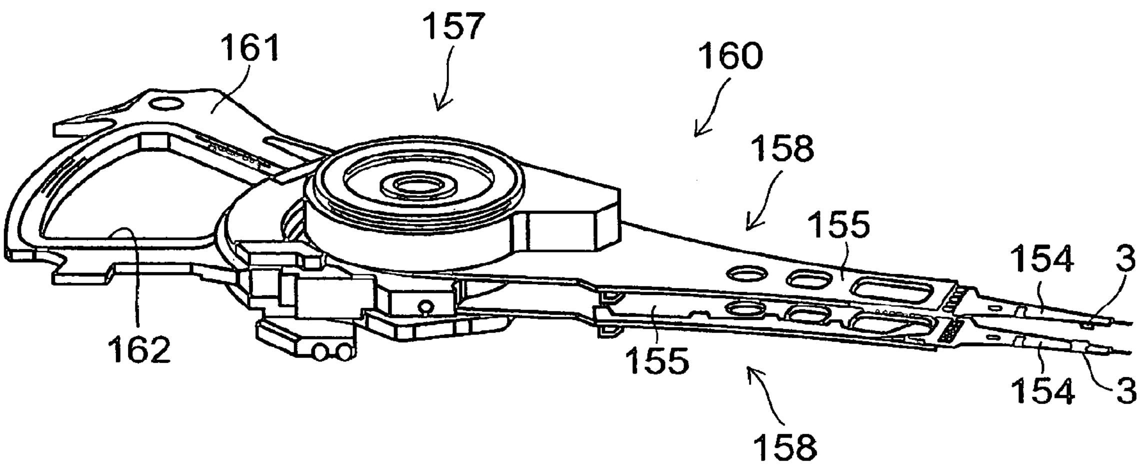


FIG. 24A

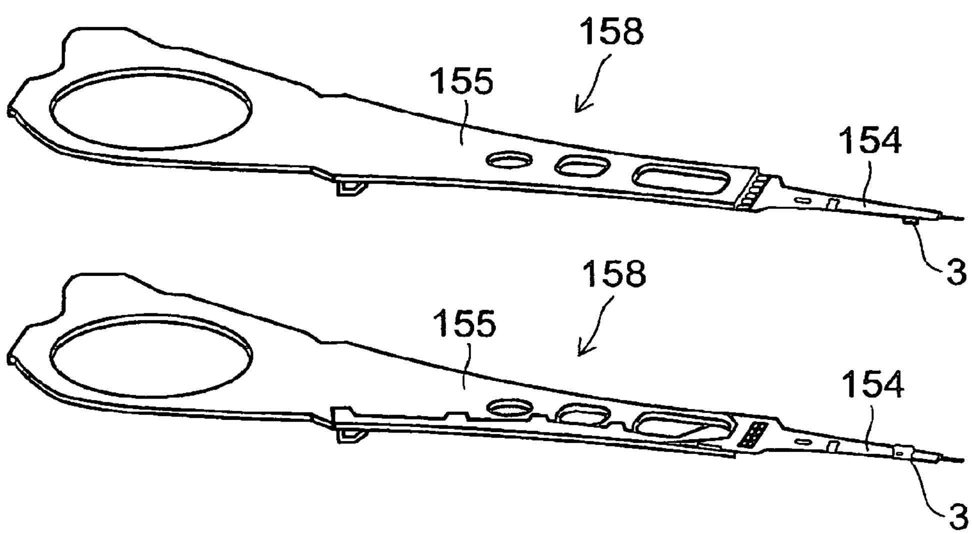


FIG. 24B

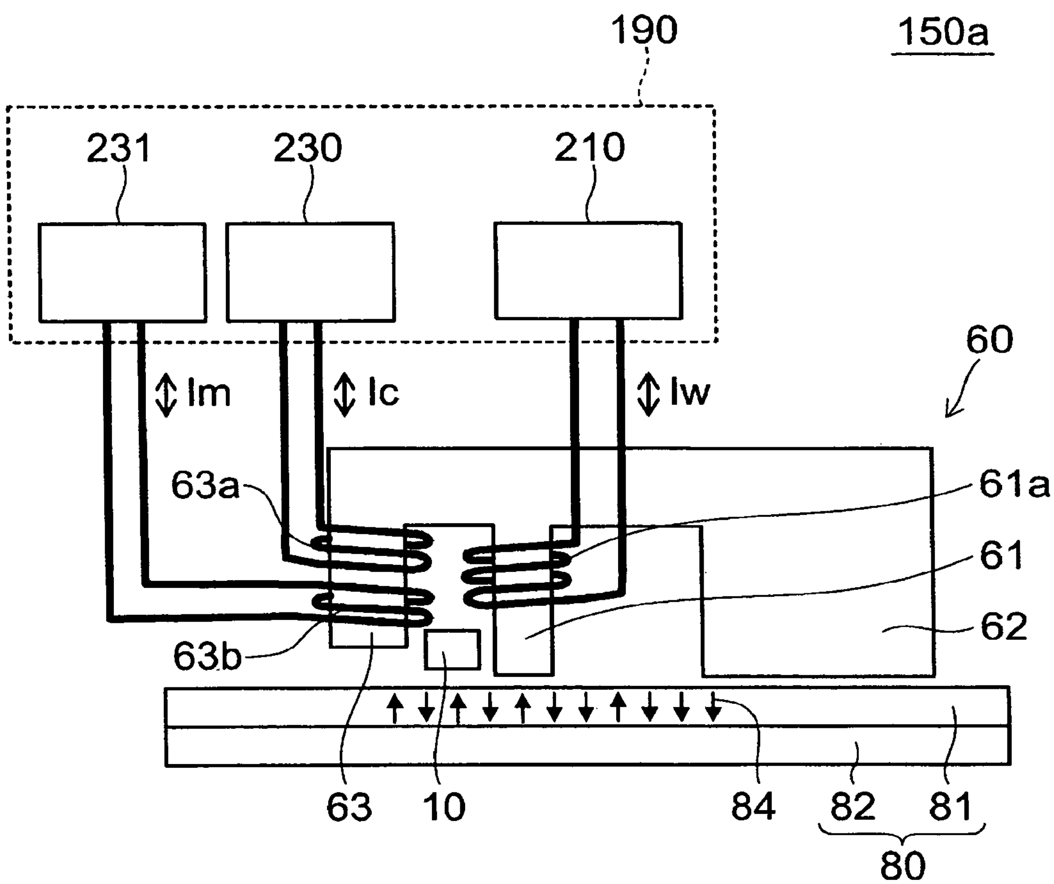
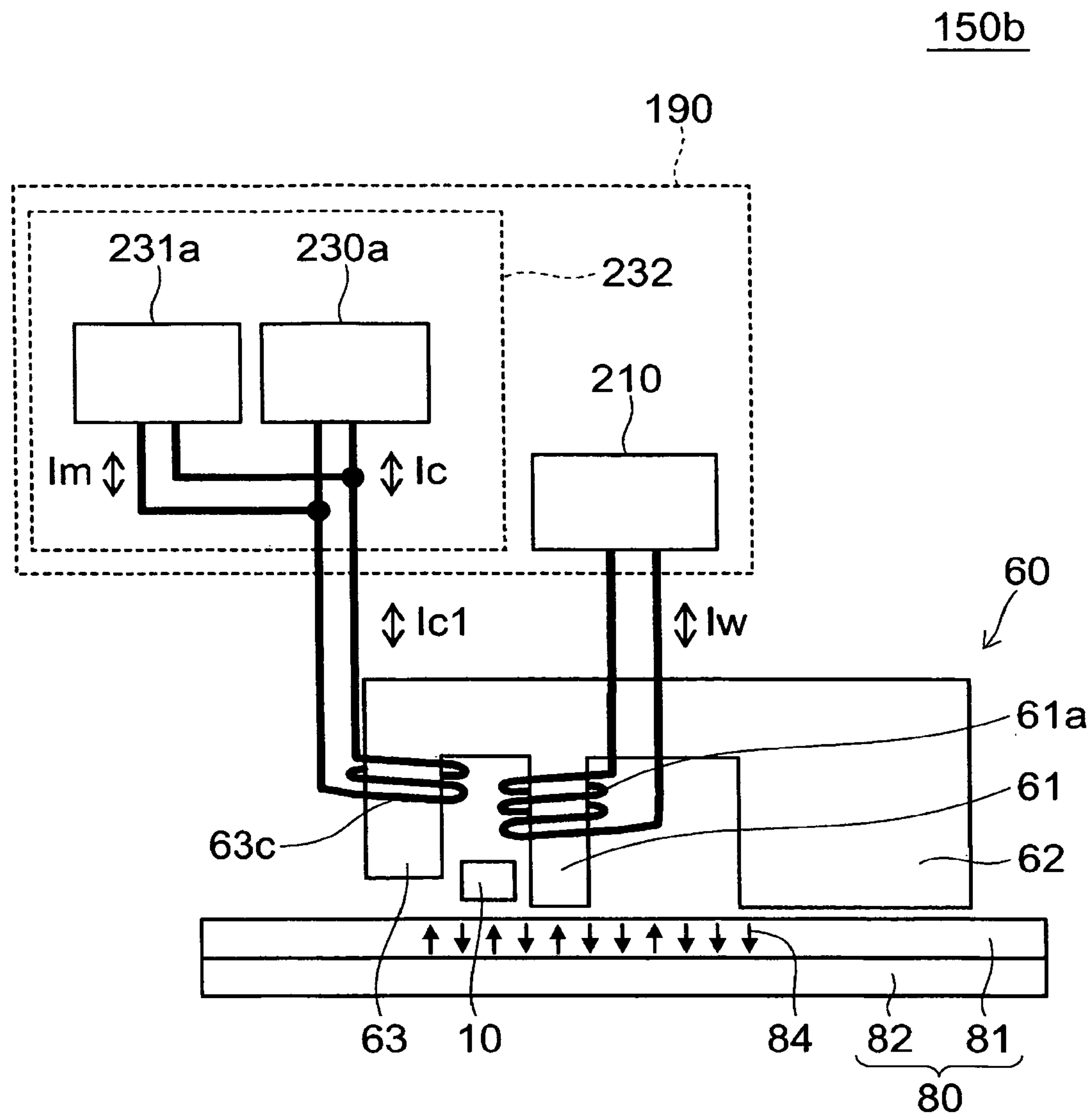


FIG. 25



150b
190
231a
230a
232
210
Im
Ic
Ic1
Iw
60
61a
61
62
63c
63
10
84
82
81
80

FIG. 26

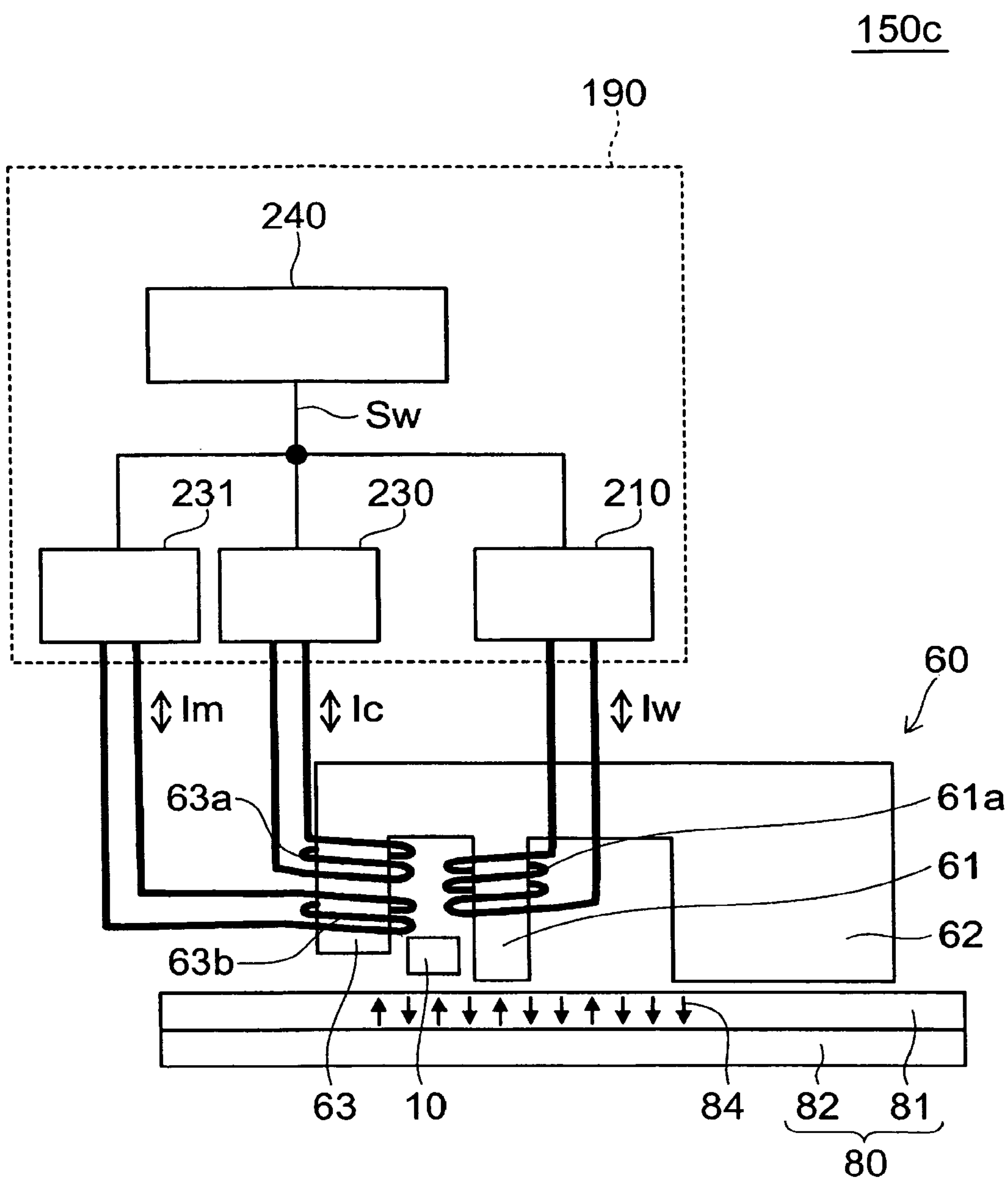

150c
190
240
Sw
231
230
210
Im
Ic
Iw
60
63a
61a
61
62
63b
63
10
84
82
81
80

FIG. 27

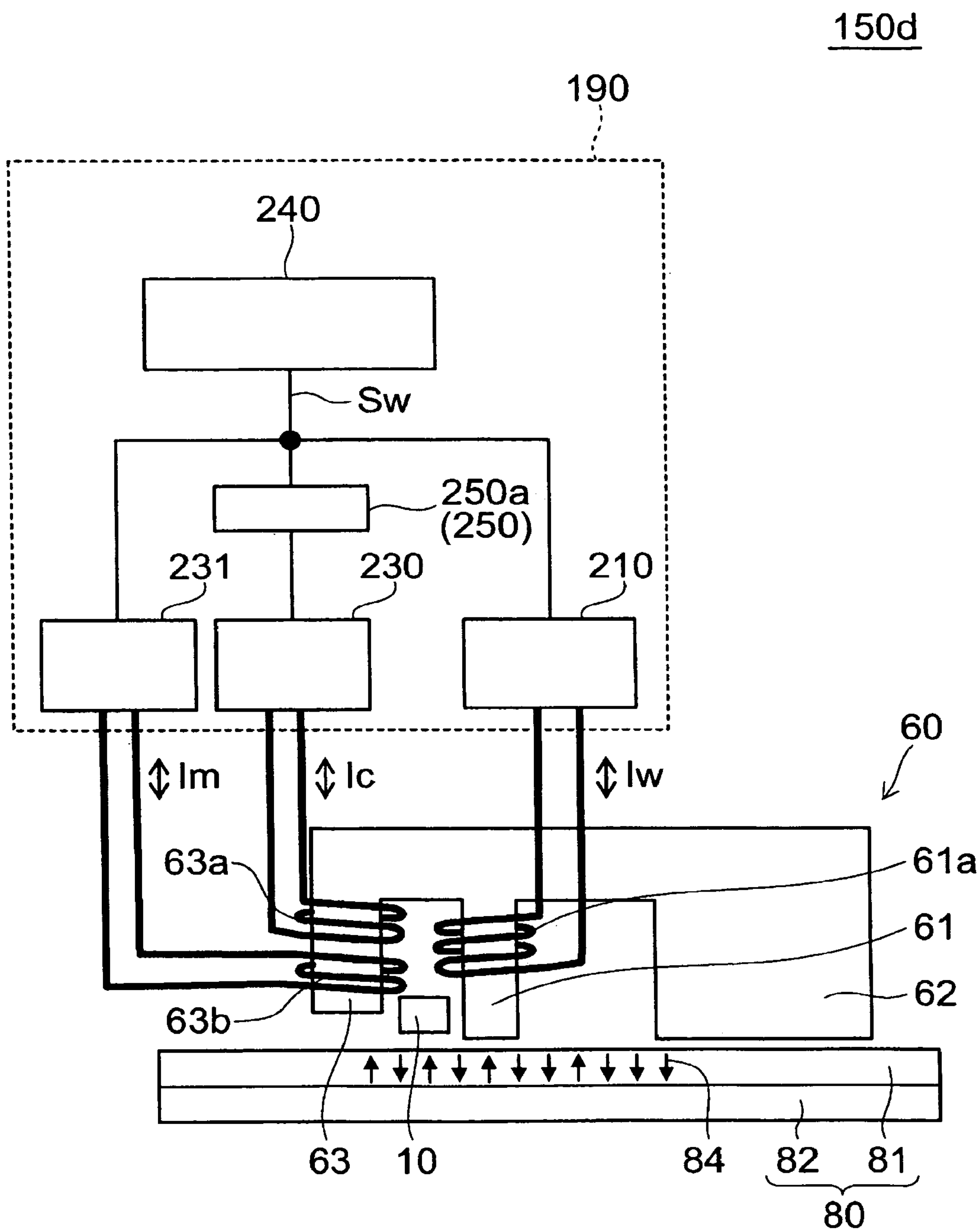
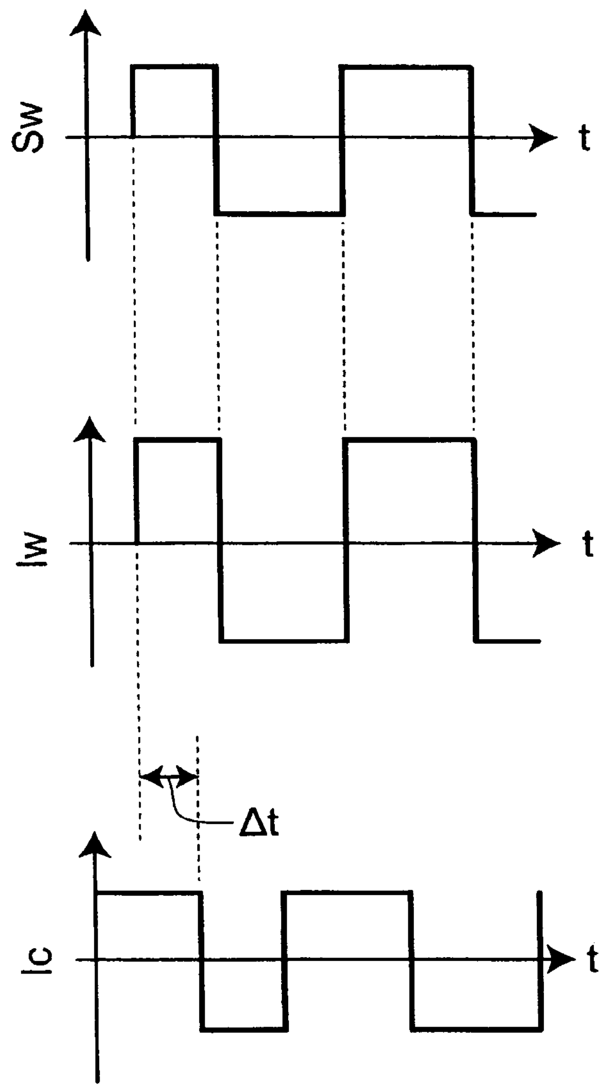

150d
190
240
Sw
250a
(250)
231
230
210
Im
Ic
Iw
60
63a
61a
61
62
63b
63
10
84
82
81
80

FIG. 28

FIG. 29A

FIG. 29B

FIG. 29C



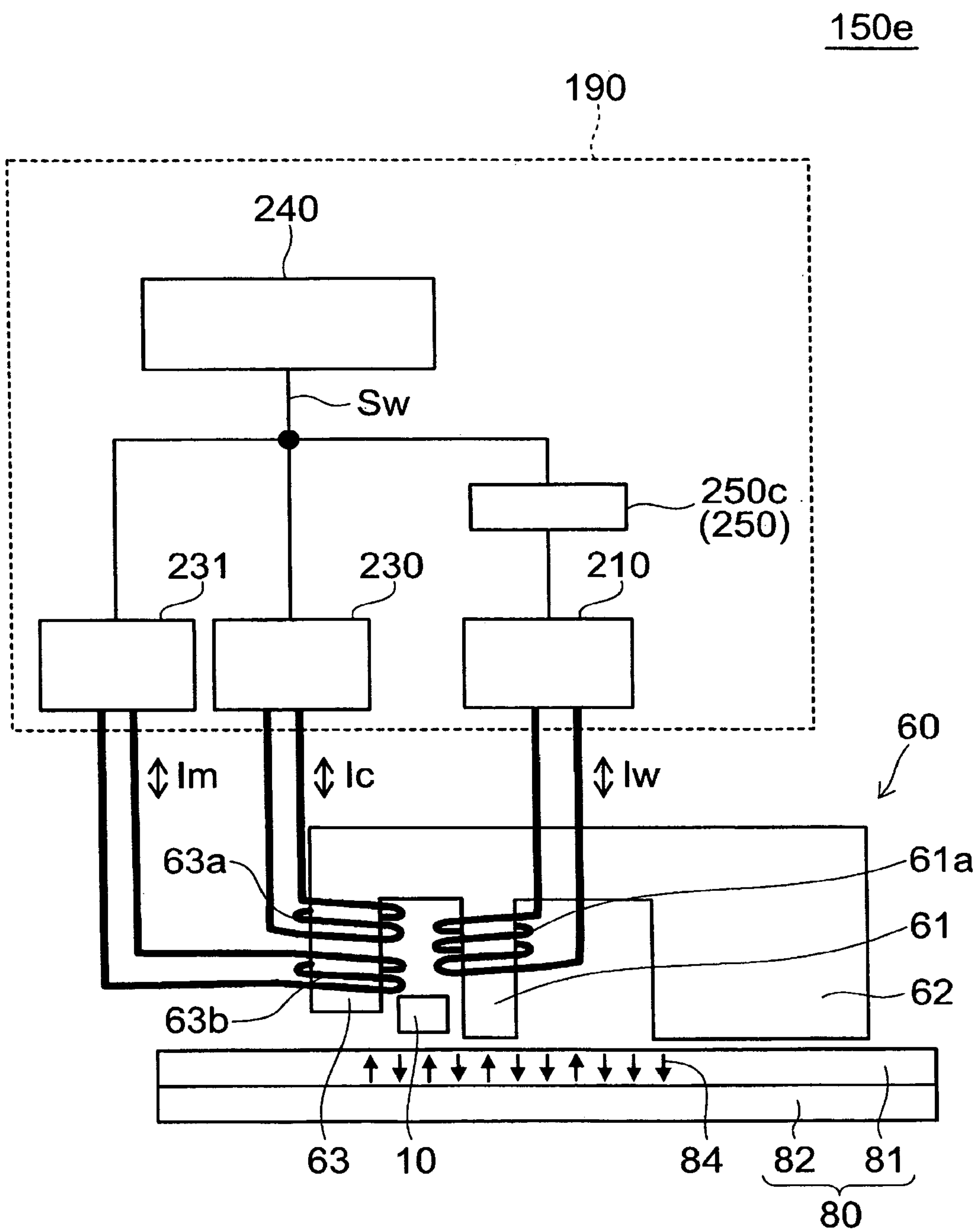

150e
190
240
Sw
250c
(250)
231
230
210
60
Im
Ic
Iw
63a
61a
61
62
63b
63
10
84
82
81
80

FIG. 30

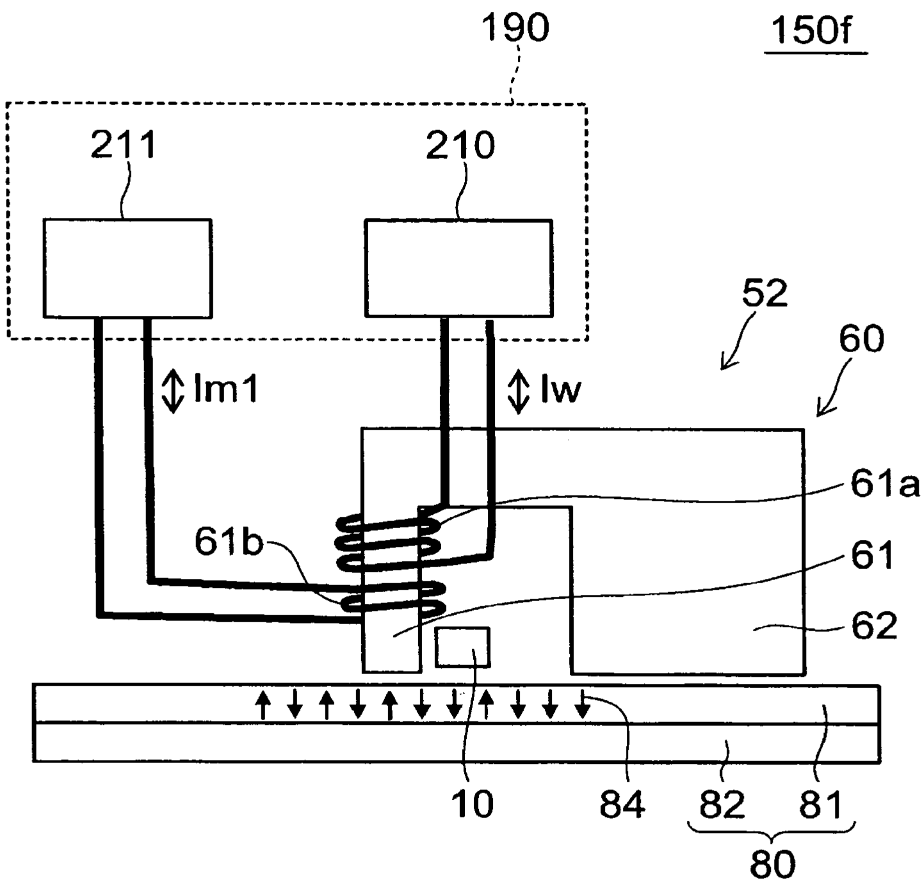


FIG. 31

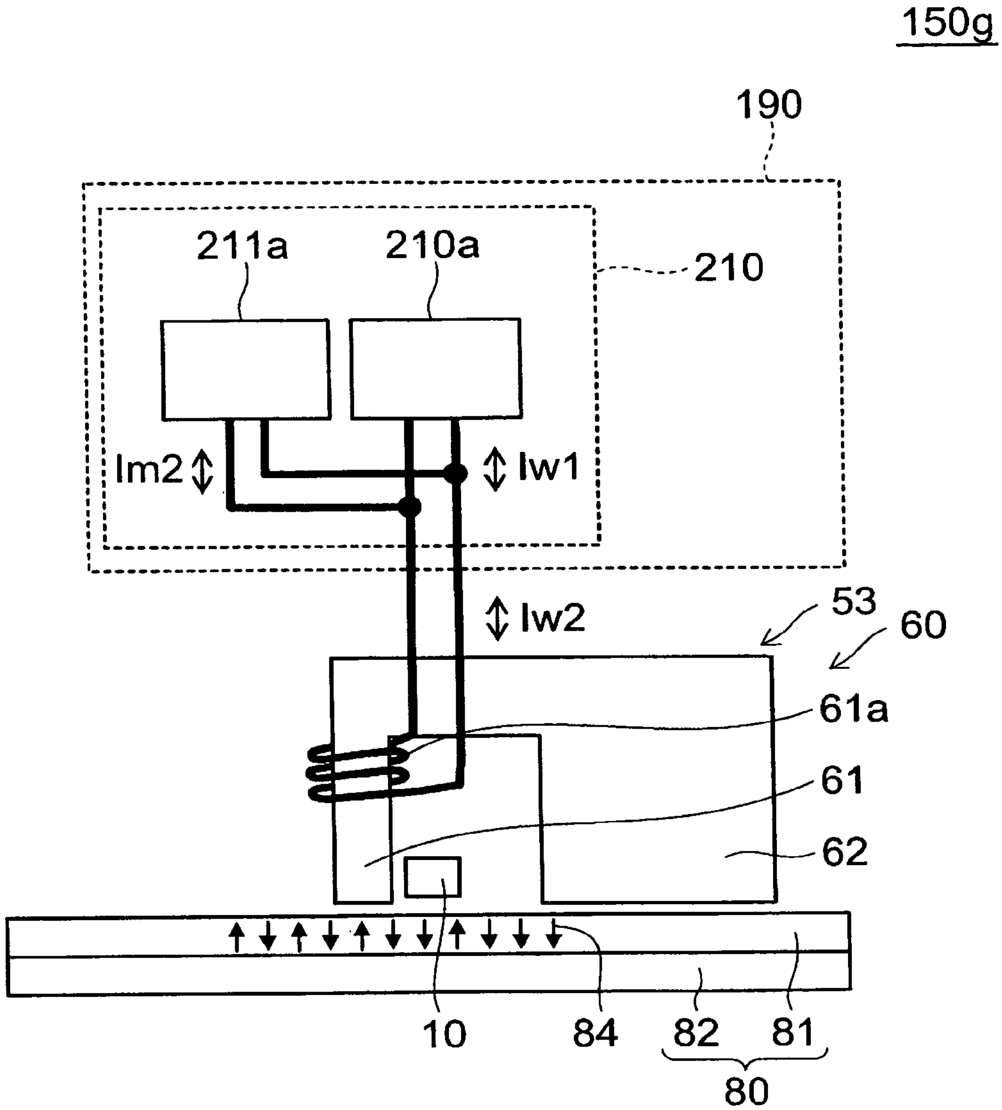


FIG. 32

FIG. 33A

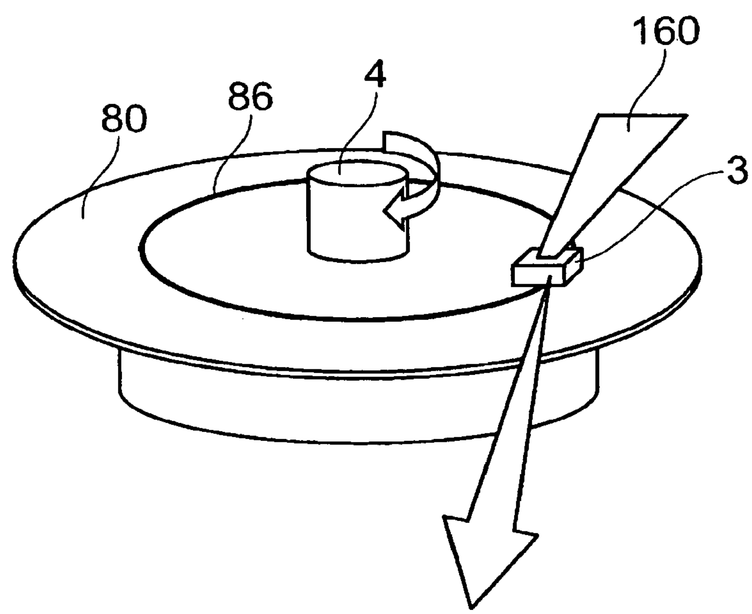


FIG. 33B

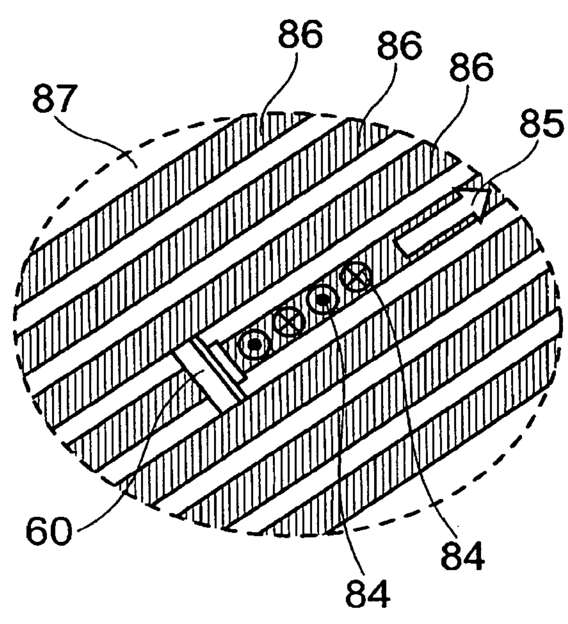


FIG. 34A

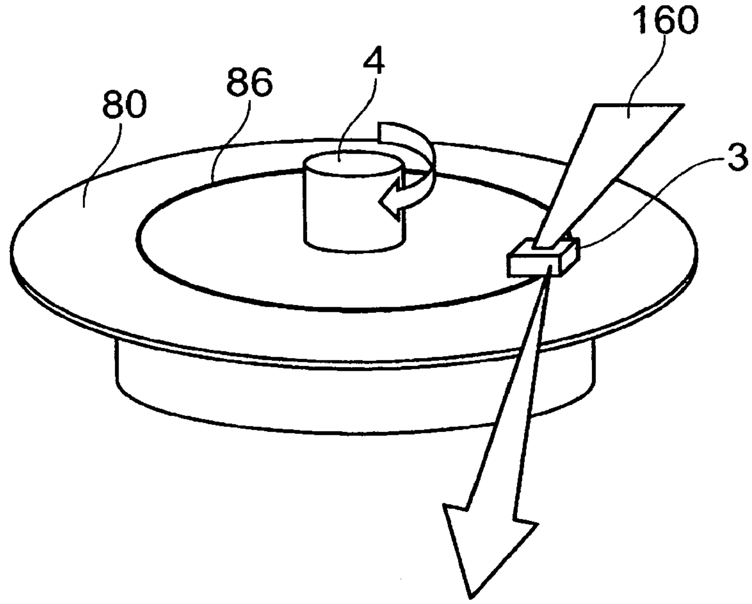
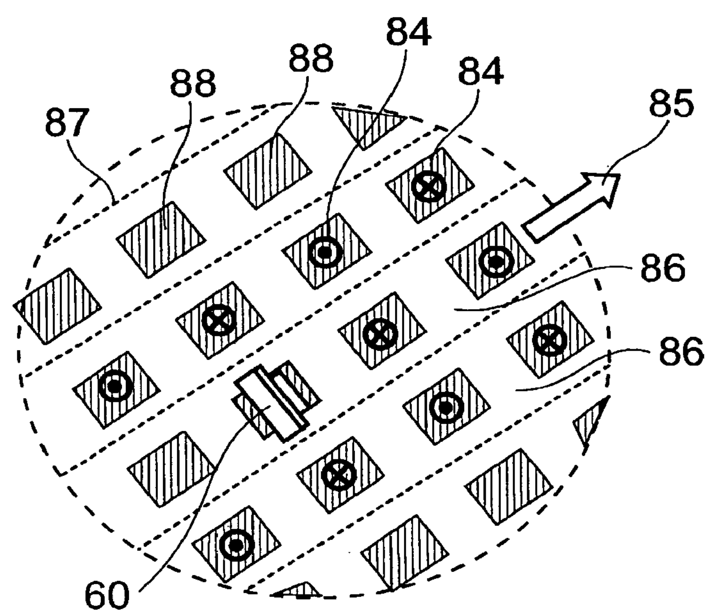


FIG. 34B



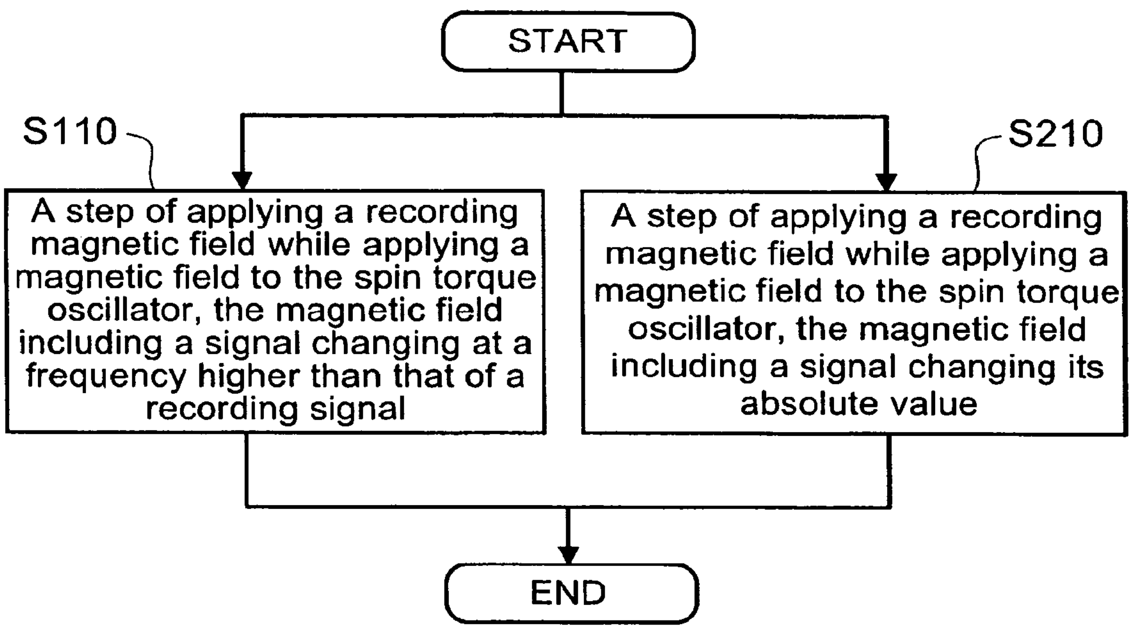

START
S110
A step of applying a recording magnetic field while applying a magnetic field to the spin torque oscillator, the magnetic field including a signal changing at a frequency higher than that of a recording signal
S210
A step of applying a recording magnetic field while applying a magnetic field to the spin torque oscillator, the magnetic field including a signal changing its absolute value
END

FIG. 35

MAGNETIC RECORDING HEAD, MAGNETIC HEAD ASSEMBLY, MAGNETIC RECORDING APPARATUS, AND MAGNETIC RECORDING METHOD

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a divisional of U.S. application Ser. No. 14/184,406, filed Feb. 19, 2014, which is a divisional of U.S. application Ser. No. 12/591,752, filed Nov. 30, 2009, now U.S. Pat. No. 8,767,346, which is based upon and claims the benefit of priority from the Japanese Patent Application No. 2008-305693, filed on Nov. 28, 2008. The entire contents of each of these applications are incorporated herein by reference.

FIELD OF THE INVENTION

The present invention relates to a magnetic recording head, a magnetic head assembly, a magnetic recording apparatus, and a magnetic recording method.

DESCRIPTION OF THE BACKGROUND

In the 1990s, the practical application of a MR (Magneto-Resistive effect) head and a GMR (Giant Magneto-Resistive effect) head has contributed to the skyrocketing of the recording density and capacity of an HDD (Hard Disk Drive). However, since the problems of heat fluctuation of a magnetic recording medium became conspicuous in the early 2000s, the speed of the increase in recording density has slowed down temporarily. Even so, a perpendicular magnetic recording was put in practical use in 2005, the perpendicular magnetic recording being more advantageous to high density recording theoretically than a longitudinal magnetic recording. This event triggers a recent growth rate of 40% for the recording density of HDD.

According to a latest demonstration experiment for HDD, 400 Gbits/inch^2 has been attained. If this trend continues strongly, a recording density of 1 Tbits/inch^2 is expected to be attained around 2012. However, it will not be easy to attain such a high recording density even employing the perpendicular magnetic recording, because the problems of heat fluctuation will still become conspicuous.

A "high-frequency magnetic field assist recording method" is proposed as a recording method which can solve this problem (U.S. Pat. No. 6,011,664). In the high-frequency magnetic field assist recording method, the magnetic field with a frequency sufficiently higher than a recording signal frequency near the resonant frequency of a magnetic recording medium is locally applied to the medium. As a result, the medium resonates, and a portion of the medium, to which the high frequency magnetic field is applied, has a coercivity half or less than that of the medium, to which no filed is applied. According to this effect, it is possible to write into a magnetic recording medium with a higher coercivity and higher anisotropy energy (Ku) by superimposing the high frequency magnetic field onto the recording field thereof. However, the method disclosed in U.S. Pat. No. 6,011,664 employs a coil to generate the high frequency magnetic field, making it difficult to efficiently apply the high frequency magnetic field to the medium.

Consequently, a method employing a spin torque oscillator has been proposed (see, for example, US-A20050023938, US-A20050219771, US-A20080019040, IEEE Trans. On Magn., Vol. 42, No. 10, PP. 2670). In the method disclosed, the spin torque oscillator includes a spin injection layer, a intermediate layer, a magnetic layer and electrodes. A direct current is passed through the spin torque oscillator via the electrodes to cause ferromagnetic resonance of magnetization in the magnetic layer, the ferromagnetic resonance being due to spin torque by spin injection. As a result, the spin torque oscillator generates the high frequency magnetic field.

Since the spin torque oscillator is about tens of nm in size, the high frequency magnetic field generated localizes in an area of about tens of nm near the spin torque oscillator. Furthermore, the in-plane component of the high frequency magnetic field allows it to cause the ferromagnetic resonance in a perpendicularly magnetized medium and to substantially reduce the coercivity of the medium. As a result, a high-density magnetic recording is performed only in a superimposed area of a recording field generated from a main magnetic pole and the high frequency magnetic field generated from the spin torque oscillator. This allows it to use a medium with a high coercivity (Hc) and high anisotropy energy (Ku). For this reason, the problem of heat fluctuation can be avoided at the time of high density recording.

In order to make a recording head for the high-frequency magnetic field assist recording, it becomes important to design and produce the spin torque oscillator capable of providing a stable oscillation with a low driving current and generating an in-plane high-frequency magnetic field to sufficiently cause a magnetic resonance of the magnetization in the medium. However, in order to acquire a very strong high frequency magnetic field, a large current must be applied to a spin torque oscillator. The large current gives rise to heating of the spin torque oscillator to deteriorate the performance thereof as a result of the heating. For this reason, a novel method is required to realize the high-frequency magnetic field assist recording using a weaker high-frequency magnetic field, i.e., a lower intensity high-frequency magnetic field.

SUMMARY OF THE INVENTION

According to a first aspect of the invention, a magnetic recording head includes a first magnetic pole, a second magnetic pole, a spin torque oscillator, a first coil, a second coil, and a third coil. The first magnetic pole applies a recording magnetic field to a magnetic recording medium. The second magnetic pole is provided parallel to the first magnetic pole. At least a portion of the spin torque oscillator is provided between the first magnetic pole and the second magnetic pole. The first coil magnetizes the first magnetic pole. A current is passed through the second coil independently of the first coil. A current is passed through the third coil independently of both the first coil and the second coil.

According to a second aspect of the invention, a magnetic recording head includes a first magnetic pole, a spin torque oscillator, and a second coil. The first magnetic pole applies a recording magnetic field to a magnetic recording medium. The spin torque oscillator is provided parallel to the first magnetic pole. The first coil magnetizes the first magnetic pole. A current is passed through the second coil independently of the first coil.

According to a third aspect of the invention, a magnetic head assembly includes the magnetic recording head according to one of the first and second aspects, a head slider, a suspension, and an actuator arm. The head slider mounts the magnetic recording head. The suspension mounts the head slider onto an end thereof. The actuator arm is connected to the other end of the suspension.

According to a fourth aspect of the invention, a magnetic recording apparatus includes a magnetic recording medium, the magnetic head assembly according to the third aspect of the invention, and a signal processor. The signal processor writes and reads a signal on the magnetic recording medium by using the magnetic recording head.

According to a fifth aspect of the invention, a magnetic recording apparatus includes a magnetic recording medium, a magnetic recording head, and a signal processor. The magnetic recording head includes a first magnetic pole, a second magnetic pole, a spin torque oscillator, a first coil, and a second coil. The first magnetic pole applies a recording magnetic field to the magnetic recording medium. The second magnetic pole is provided parallel to the first magnetic pole. At least a portion of the spin torque oscillator is provided between the first magnetic pole and the second magnetic pole. The first coil magnetizes the first magnetic pole. A current is passed through the second coil independently of the first coil. The signal processor writes and reads a signal on the magnetic recording medium by using the magnetic recording head. The signal processor includes a first current circuit and a second current circuit. The first current circuit supplies a recording current to the first coil. The recording current includes a recording signal to be recorded on the magnetic recording medium. The second current circuit supplies a modulating current to the second coil. In addition, the modulating current includes either one of a signal changing at a frequency higher than that of the recording signal, and a signal having the same frequency as the recording signal to change an absolute value thereof in one cycle.

According to a sixth aspect of the invention, a magnetic recording apparatus includes a magnetic recording medium, a magnetic recording head, and a signal processor. The magnetic recording head includes a first magnetic pole, a spin torque oscillator, and a first coil. The first magnetic pole applies a recording magnetic field to the magnetic recording medium. The spin torque oscillator is arranged parallel to the first magnetic pole. The first coil magnetizes the first magnetic pole. The signal processor writes and reads a signal on the magnetic recording medium by using the magnetic recording head, and includes a first current circuit to supply a recording current to the first coil. The recording current includes a recording signal to be recorded on the magnetic recording medium. In addition, the recording current includes either one of a signal changing at a frequency higher than that of the recording signal and a signal having the same frequency as the recording signal to change an absolute value thereof in one cycle.

According to a seventh aspect of the invention, a method for recording information onto a magnetic recording medium includes recording information onto the magnetic recording medium while applying a magnetic field to a spin torque oscillator arranged near a magnetic pole to record information onto the magnetic recording medium. The magnetic field includes either one of a first signal changing at a frequency higher than that of a recording signal to be recorded on the magnetic recording medium and a second signal having the same frequency as the recording signal to change an absolute value thereof in one cycle.

BRIEF DESCRIPTION OF DRAWINGS

FIG. **1** is a perspective view schematically illustrating a configuration of a magnetic recording head according to a first embodiment of the invention.

FIG. **2** is a perspective view schematically illustrating a configuration of a slider to carry the magnetic recording head according to the first embodiment of the invention.

FIG. **3** is a perspective view schematically illustrating a configuration of a spin torque oscillator to be employed for a magnetic recording head according to the first embodiment of the invention.

FIG. **4** is a perspective view schematically illustrating a configuration of a substantial portion of a magnetic recording head according to the first embodiment of the invention.

FIGS. **5**A to **5**D are schematic views illustrating currents to be passed through a magnetic recording head according to the first embodiment of the invention.

FIGS. **6**A to **6**E are schematic views illustrating magnetic fields generated in a magnetic recording head according to the first embodiment of the invention.

FIG. **7** is a graph illustrating a characteristic of a magnetic recording head according to the first embodiment of the invention.

FIG. **8** is a graph schematically illustrating a characteristic of a magnetic recording head according to the first embodiment of the invention.

FIGS. **9**A to **9**C are schematic views illustrating an operation of a magnetic recording head according to the first embodiment of the invention.

FIG. **10**A is a schematic view illustrating an arrangement of a main magnetic pole in a writing head portion of a magnetic recording head according to the first embodiment of the invention.

FIG. **10**B is a graph illustrating a simulation of a characteristic of a magnetic recording head according to the first embodiment of the invention.

FIG. **11** is a perspective view schematically illustrating a structure of a substantial portion of another magnetic recording head according to the first embodiment of the invention.

FIGS. **12**A to **12**E are schematic views illustrating currents to be passed through another magnetic recording head according to the first embodiment of the invention, and magnetic fields to be generate by the currents.

FIG. **13** is a perspective view schematically illustrating a structure of a substantial portion of another magnetic recording head according to the first embodiment of the invention.

FIG. **14** is a schematic view illustrating a structure of a substantial portion of another magnetic recording head according to the first embodiment of the invention.

FIG. **15** is a sectional view cut along the line XV-XV of FIG. **14**.

FIG. **16** is a perspective view schematically illustrating a structure of a substitutional portion of a magnetic recording head according to a second embodiment of the invention.

FIGS. **17**A to **17**E are schematic views illustrating currents to be passed through the magnetic recording head according to the second embodiment of the invention, and magnetic fields to be generated by the currents.

FIG. **18** is a perspective view schematically illustrating a structure of a substantial portion of a magnetic recording head according to a third embodiment of the invention.

FIGS. **19**A to **19**D are schematic views illustrating currents to be passed through the magnetic recording head according to the third embodiment of the invention, and magnetic fields to be generated by the currents.

FIGS. **20**A to **20**F are schematic views illustrating external magnetic fields applied to a spin torque oscillator of the magnetic recording head according to the third embodiment of the invention.

FIGS. **21**A to **21**D are schematic views illustrating currents to be passed through the magnetic recording head according to a fourth embodiment of the invention.

FIGS. **22**A to **22**E are schematic views illustrating magnetic fields to be generated in the magnetic recording head according to the fourth embodiment of the invention.

FIG. **23** is a perspective view schematically illustrating a configuration of a magnetic recording apparatus according to a fifth embodiment of the invention.

FIGS. **24**A and **24**B are typical perspective views illustrating a configuration of a portion of the magnetic recording apparatus according to the fifth embodiment of the invention.

FIG. **25** is a schematic view illustrating a configuration of a portion of another magnetic recording apparatus according to the fifth embodiment of the invention.

FIG. **26** is a schematic view illustrating a configuration of a portion of another magnetic recording apparatus according to the fifth embodiment of the invention.

FIG. **27** is a schematic view illustrating a configuration of another magnetic recording apparatus according to the fifth embodiment of the invention.

FIG. **28** is a schematic view illustrating a configuration of another magnetic recording apparatus according to the fifth embodiment of the invention.

FIGS. **29**A to **29**C are schematic views illustrating operation currents for another magnetic recording apparatus according to the fifth embodiment of the invention.

FIG. **30** is a schematic view illustrating a configuration of another magnetic recording apparatus according to the fifth embodiment of the invention.

FIG. **31** is a schematic view illustrating a partial configuration of another magnetic recording apparatuses according to the fifth embodiment of the invention.

FIG. **32** is a schematic view illustrating a configuration of another magnetic recording apparatus according to the fifth embodiment of the invention.

FIGS. **33**A and **33**B are typical perspective views illustrating configurations of the magnetic recording medium of a magnetic recording apparatus according to the fifth embodiment of the invention.

FIGS. **34**A and **34**B are typical perspective views illustrating configurations of another magnetic recording medium of a magnetic recording apparatus according to the fifth embodiment of the invention.

FIG. **35** is a flow chart illustrating a magnetic recording method according to a sixth embodiment of the invention.

DETAILED DESCRIPTION OF THE EMBODIMENTS

Embodiments of the present invention are explained below with reference to accompanying drawings. The drawings are conceptual. Therefore, a relationship between the thickness and width of each portion and a proportionality factor among respective portions are not necessarily the same as an actual thing. Even when the same portions are drawn, their sizes or proportionality factors can be represented differently from each other depending on the drawings. The embodiments of the present invention will be described below with reference to accompanying drawings. Wherever possible, the same reference numerals will be used to denote the same or like portions throughout the detailed description and the figures.

First Embodiment

A magnetic recording head according to a first embodiment of the present invention is explained assuming that the head records on a perpendicular magnetic recording medium including magnetic grains (magnetic crystal grains). FIG. **1** is a perspective view schematically illustrating a configuration of the magnetic recording head according to the first embodiment of the invention. FIG. **2** is a perspective view schematically illustrating a configuration of a slider to carry the magnetic recording head according to the first embodiment of the invention. FIG. **3** is a perspective view schematically illustrating a configuration of a spin torque oscillator to be employed for the magnetic recording head according to the first embodiment of the invention. FIG. **4** is a perspective view schematically illustrating a configuration of a substantial portion of the magnetic recording head according to the first embodiment of the invention.

As illustrated in FIG. **1**, the magnetic recording head according to the first embodiment of the invention is provided with the following:

- a main magnetic pole **61** (a first magnetic pole) to apply a recording magnetic field to a magnetic recording medium **80**; and
- a spin torque oscillator **10** provided between the main magnetic pole **61** and a controlling magnetic pole **63** (a second magnetic pole) which is arranged in a direction parallel to the main magnetic pole **61**.

The magnetic recording head is further provided with the following:

- a main magnetic pole coil **61***a* (a first coil) to magnetize the main magnetic pole **61**;
- a controlling magnetic pole coil **63***a* (a third coil) to magnetize the controlling magnetic pole **63**; and
- a controlling magnetic pole modulation coil **63***b* (a modulating coil, i.e., a second coil) to magnetize the controlling magnetic pole **63**.

It is possible to pass a current through the controlling magnetic pole **63***a* independently of the main magnetic pole coil **61***a* and the controlling magnetic pole modulation coil **63***b*. It is also possible to pass a current through the controlling magnetic pole modulation coil **63***b* independently of the main magnetic pole coil **61***a* and the controlling magnetic pole coil **63***a*.

In a specific example illustrated in FIG. **1**, the spin torque oscillator **10** is provided between the main magnetic pole **61** and the controlling magnetic pole **63**. Alternatively, the controlling magnetic pole **63** may be provided in a more recessed manner than a medium-facing surface **61***s* of the main magnetic pole **61** as will be mentioned later. In this alternative case, a portion of the spin torque oscillator **10** is provided between the main magnetic pole **61** and the controlling magnetic pole **63**. Thus, at least a portion of the spin torque oscillator **10** may be provided between the main magnetic pole **61** and the controlling magnetic pole **63**.

The above-mentioned main magnetic pole **61**, the spin torque oscillator **10**, the controlling magnetic pole **63**, the main magnetic pole coil **61***a*, the controlling magnetic pole coil **63***a*, and the controlling magnetic pole modulation coil **63***b* are included in a writing head portion **60**.

The writing head portion **60** can further include a return path (shield) **62**. In the specific example illustrated in FIG. **1**, the return path **62** is arranged on the side of a read section **70** across the main magnetic pole **61** so as to be easily viewable, but an arrangement of the return path **62** is not definite but optional. Alternatively, the return path **62** may be formed integrally with a side shield mentioned later.

In addition, the magnetic recording head is further provided with the read section **70** as illustrated in FIG. **1**. The read section **70** includes a first magnetic shield layer **72***a*, a second magnetic shield layer **72***b*, and a magnetic read element **71**. The magnetic read element **71** is provided between the first magnetic shield layer **72***a* and the second magnetic shield layer **72***b*. Each element of the above-mentioned read section **70** and each element of the above-mentioned writing head portion **60** are separated by insulators, such as alumina, etc. not illustrated in the figure. As the magnetic read element **71**, a GMR element or a TMR (Tunnel Magneto-Resistive effect) element can be employed. In order to enhance a reproducing resolution, the magnetic read element **71** is disposed between the first and second magnetic shield layers **72***a*, **72***b*.

And as illustrated in FIG. **1**, the magnetic recording medium **80** is provided to face the medium-facing surface **61***s* of a magnetic recording head **51**. The medium-facing surface **61***s* of the magnetic recording head **51** may be a principal plane of the main magnetic pole **61** facing the magnetic recording medium **80** to be disposed for the magnetic recording head **51**.

For example, as shown in FIG. **2**, the magnetic recording head **51** is mounted to a head slider **3**. The head slider **3** includes Al_2O_3/TiC, etc., and is designed to be produced so that the head slider **3** is capable of moving relatively to the magnetic recording medium **80**, e.g., a magnetic disk with flying thereon or contacting thereto.

The head slider **3** has an air inflow side **3**A and an air outflow side **3**B. The magnetic recording head **51** is provided to the side surface of the air outflow side **3**B, etc. Thereby, the magnetic recording head **51** mounted to the head slider **3** moves relatively to the magnetic recording medium **80** with flying thereon or contacting therewith.

As shown in FIG. **1**, the magnetic recording medium **80** has a medium substrate **82** and a magnetic recording layer **81** provided on the medium substrate **82**. Magnetization **83** of the magnetic recording layer **81** is controlled in a predetermined direction by a magnetic field applied from the writing head portion **60** to thus perform write-in. On the other hand, the read section **70** reads a direction of the magnetization **83** of the magnetic recording layer **81**.

Here, as shown in FIG. **1**, X-axis is normal to a plane across which the main magnetic pole **61** faces the controlling magnetic pole **63**, and has a direction from the controlling magnetic pole **63** to the main magnetic pole **61**. Y-axis is normal to X-axis, and parallel to the medium-facing surface **61***s*. Z-axis is normal to both X-axis and Y-axis. Therefore, Z-axis is normal to the medium-facing surface **61***s*.

As shown in FIG. **3**, the spin torque oscillator **10** provided to the magnetic recording head **51** has an oscillation layer **10***a* (a first magnetic layer), a spin injection layer **30** (a second magnetic layer), and an intermediate layer **22** disposed between the oscillation layer **10***a* and the spin injection layer **30**. Then, the oscillation layer **10***a* and the spin injection layer **30** are configured to have a coercivity smaller than a magnetic field applied from the main magnetic pole **61**.

Thus, the spin torque oscillator **10** includes a laminated structure **25** of the oscillation layer **10***a*, the spin injection layer **30**, and the nonmagnetic intermediate layer **22** disposed between the oscillation layer **10***a* and the spin injection layer **30**.

The principal plane of these layers is normal to X-axis, and the lamination direction is parallel to X-axis. The invention is not limited to the above. Alternatively, the lamination direction of the laminated structure **25** may be parallel to Y-axis.

The spin torque oscillator **10** can be provided with a pair of electrodes (a first electrode **41** and a second electrode **42**) to be capable of passing a current through the laminated structure **25**. That is, the first and second electrodes **41**, **42** are provided to the side of the oscillation layer **10***a* of the laminated structure **25** and the side of the spin injection layer **30** of the laminated structure **25**, respectively.

In the example illustrated in FIG. **3**, the side of the first electrode **41**, i.e., the side of the oscillation layer **10***a* is arranged on the side of the main magnetic pole **61**, and the side of the second electrode **42**, i.e., the side of the spin injection layer **30** is arranged on the side of the controlling magnetic pole **63**. Thereby, the oscillation layer **10***a* and the main magnetic pole **61** are close to each other. Furthermore, a high frequency magnetic field Hac generated from the spin torque oscillator **10** and a recording magnetic field Hw generated from the main magnetic pole **61** are easily superimposed on each other to be applied to the magnetic recording medium **80**, thus allowing it to perform a high frequency magnetic field assist recording more effectively. However, the invention is not limited to the above. Alternatively, the side of the second electrode **42**, i.e., the side of the spin injection layer **30** may be arranged on the side of the main magnetic pole **61**, and the side of the first electrode **41**, i.e., the side of the oscillation layer **10***a* may be arranged on the side of the controlling magnetic pole **63**, depending on designs of each constituent and materials selected.

In the spin torque oscillator **10**, a current is passed through the first and second electrodes **41**, **42** to generate a high frequency magnetic field from the oscillation layer **10***a*. A driving current for the spin torque oscillator **10** is preferably from 5×10^7 A/cm^2 to 1×10^9 A/cm^2, and is controlled to acquire a desired oscillation state.

Materials, which are hard to be oxidized and have low resistances, such as Ti, Cu, etc. are employed for the first and second electrodes **41**, **42**. Alternatively, at least either one of the first and second electrodes **41**, **42** mentioned above may double as at least one of the main magnetic pole **61** and the controlling magnetic pole **63**. Either one of the first and second electrode **41**, **42** may be modified to double as the return path **62**.

Materials with high spin transmissivity, such as Cu, Au, and Ag, can be used for the intermediate layer **22**. The intermediate layer **22** is preferably one atomic layer to 5 nm in thickness. This allows it to adjust exchange coupling between the oscillation layer **10***a* and the spin injection layer **30**.

The oscillation layer **10***a* includes a high-Bs soft magnetic material (FeCo/NiFe laminated film) to generate a magnetic field during oscillation. The thickness of the oscillation layer **10***a* is preferably from 5 nm to 20 nm.

The spin injection layer **30** is made of a CoPt alloy with its magnetization oriented perpendicularly to the film plane. The thickness of the spin injection layer **30** is preferably from 2 nm to 60 nm.

The spin injection layer **30** and the oscillation layer **10***a* can be a soft magnetic layer selected from the group consisting of CoFe, CoNiFe, NiFe, CoZrNb, FeN, FeSi, FeAlSi, FeCoAl, FeCoSi, CoFeB, etc. which have a relatively high saturation magnetic flux density and magnetic anisotropy in a direction parallel to the film plane, or a CoCr-based or CoIr-based magnetic alloy film with its magnetization oriented in a direction parallel to the film plane. It is also possible to suitably use a material layer well oriented perpendicularly such as a CoCrPt, CoCrTa, CoCrTaPt, CoCrTaNb, or other CoCr-based magnetic layer, a TbFeCo or other RE-TM amorphous alloy magnetic layer, a Co/Ni, Co/Pd, Co/Pt, CoCrTa/Pd, or other Co artificial lattice magnetic layer, a CoPt-based or FePt-based alloy magnetic layer, or a SmCo-based alloy magnetic layer, which have the magnetization oriented in a direction perpendicular to the film plane. Two or more of the above materials laminated may be employed. This allows it to easily adjust the saturation magnetic flux density (Bs) and the anisotropy magnetic field (Hk) of the oscillation layer **10***a* and the spin injection layer **30**.

The main magnetic pole **61**, the controlling magnetic pole **63**, and the return path **62** can be a soft magnetic layer selected from the group consisting of FeCo, CoFe, CoNiFe, NiFe, CoZrNb, FeN, FeSi, and FeAlSi, etc. having a relatively high saturation magnetic flux density.

Alternatively, the material on the side of the medium-facing surface **61***s* of the main magnetic pole **61** is different from that of any portions other than the portion on the side of the medium-facing surface **61***s* in the main magnetic pole **61** and the controlling magnetic pole **63**. That is, in order to increase a magnetic field applied to the magnetic recording medium **80** or a magnetic field generated by the spin torque oscillator **10**, FeCo, CoNiFe, FeN, etc. with a particularly large saturation magnetic flux density are employed for the materials of the portion on the side of the medium-facing surface **61***s* of the main magnetic pole **61**. Any portions other than the portion on the side of the medium-facing surface **61***s* of the main magnetic pole **61** may include FeNi, etc. with a particularly high permeability. Alternatively, the size of the portion on the side of the medium-facing surface **61***s* of the main magnetic pole **61** may be smaller in order to enlarge a magnetic field applied to the magnetic recording medium **80** or a magnetic field generated by the spin torque oscillator **10**. Thereby, magnetic flux concentrates on the side of the medium-facing surface **61***s*, thereby allowing it to generate a high magnetic field.

Materials, which are hard to be oxidized and have low resistances, such as Ti, Cu, etc. may be employed for the main magnetic pole coil **61***a*, the controlling magnetic pole coil **63***a*, and the controlling magnetic pole modulation coil **63***b*.

As illustrated in FIG. **4**, the main magnetic pole coil **61***a* magnetizes the main magnetic pole **61**. The controlling magnetic pole modulation coil **63***b* magnetizes the controlling magnetic pole **63**, and it is possible to pass a current through the controlling magnetic pole modulation coil **63***b* independently of the main magnetic pole coil **61***a*. The controlling magnetic pole coil **63***a* magnetizes the controlling magnetic pole **63**. It is possible to pass a current through the controlling magnetic pole modulation coil **63***b* independently of the main magnetic pole coil **61***a* and the controlling magnetic pole modulation coil **63***b*.

For example, as illustrated in FIG. **4**, the main magnetic pole coil **61***a* is connected to a recording current circuit **210** (a first current circuit). Then the controlling magnetic pole coil **63***a* is connected to an controlling magnetic pole current circuit **230** (a third current circuit). The controlling magnetic pole modulation coil **63***b* is connected to a controlling magnetic pole modulation current circuit **231** (a modulating current circuit, i.e., a second current circuit).

This allows it to apply a magnetic field (an external magnetic field Hext) to the spin torque oscillator **10**. The external magnetic field Hext includes a modulation signal changing at a frequency higher than a recording signal of the recording magnetic field applied to the magnetic recording medium **80**. The external magnetic field Hext is applied to the spin torque oscillator **10** to allow it to modulate the frequency fs of the high frequency magnetic field Hac generated in the spin torque oscillator **10**, thereby making the magnetic recording medium **80** resonate easily with the high frequency magnetic field Hac. This provides a magnetic recording head capable of performing a stable high-frequency magnetic field assist recording using a lower intensity high-frequency magnetic field Hac.

An operation of a magneto-resistive effect element recording head according to the first embodiment is explained in detail below. FIGS. **5**A to **5**D are schematic views illustrating currents to be passed through the magnetic recording head according to the first embodiment of the invention. FIG. **5**A illustrates a recording signal Sw to record information on the magnetic recording medium **80** via the main magnetic pole **61**. FIG. **5**B illustrates a recording current Iw supplied to the main magnetic pole coil **61***a*. FIG. **5**C illustrates an controlling current Ic supplied to the controlling magnetic pole coil **63***a*. FIG. **5**D illustrates an controlling magnetic pole modulation current Im supplied to the controlling magnetic pole modulation coil **63***b*.

As shown in FIG. **5**A, the recording signal Sw changes with time based on information to be recorded on the magnetic recording medium **80**.

As illustrated in FIG. **5**B, the recording current Iw changes based on the recording signal Sw. The main magnetic pole **61** applies the recording magnetic field to the magnetic recording medium **80** using the recording current Iw. Alternatively, the polar character of the recording current Iw may be opposite to that of the recording signal Sw depending on a winding manner of the main magnetic pole coil **61***a*, and there may be a phase shift between the recording current Iw and the recording signal Sw. In this embodiment, it is assumed that the recording current Iw and the recording signal Sw have the same polar character, and there is no phase shift therebetween.

On the other hand, as illustrated in FIG. **5**C, the controlling current Ic is maintained to be constant by compensating a difference in recording conditions for the magnetic recording medium **80** or a variation in the oscillation frequency of the spin torque oscillator **10**. The difference can occur between the inner and outer circumferences of the magnetic recording medium **80**. The variation can occur depending on a variation in manufacturing processes of the spin torque oscillator **10**. In this example, the frequency of the controlling current Ic is the same as that of the recording signal Sw, i.e., the frequency of the recording current Iw. In addition, there may be phase shift between the controlling current Ic and the recording current Iw, or between the controlling current Ic and the recording signal Sw. However, a case without the phase shift is explained below.

As illustrated in FIG. **5**D, the controlling magnetic pole modulation current Im oscillates at a frequency higher than that of the recording current Iw. That is, the controlling magnetic pole modulation current Im includes a modulation signal Sm which changes at a frequency higher than that of the recording signal Sw of the recording magnetic field Hw. For example, the frequency of the controlling magnetic pole modulation current, i.e., the frequency of the modulation signal Sm is set to be higher than 1.5 GHz.

FIGS. **6**A to **6**E are schematic views illustrating magnetic fields generated in the magnetic recording head according to the first embodiment of the invention. FIG. **6**A illustrates the recording magnetic field Hw, which is generated from the magnetic pole coil **61***a* of the magnetic pole **61**, to be applied to the magnetic recording medium **80**. FIG. **6**B illustrates a main magnetic pole application field Hs generated from the main magnetic pole **61** to be applied to the spin torque oscillator **10**. FIG. **6**C illustrates the controlling magnetic field component Hc generated from the controlling magnetic pole **63** of the controlling magnetic pole coil **63***a*. FIG. **6**D illustrates a modulating magnetic field component Hm generated from the controlling magnetic pole modulation coil **63***b* of the controlling magnetic pole **63**. FIG. **6**E illustrates the external magnetic field Hext of the respective magnetic fields mentioned above which are superimpose on each other to be applied to the spin torque oscillator.

As illustrated in FIG. **6**A, the magnetic field based on the recording signal Sw, i.e., the recording current Iw is generated from the main magnetic pole **61**, and the magnetic field is applied as the recording magnetic field Hw to the magnetic recording medium **80**.

Then, as illustrated in FIG. **6**B, a portion of the magnetic field generated from the main magnetic pole **61** is applied as a main magnetic pole application magnetic field Hs to the spin torque oscillator **10**. Thus, a portion of the magnetic field generated from the main magnetic pole **61** is the recording magnetic field Hw and the other portion is the main magnetic pole application magnetic field Hs. Therefore, the main magnetic pole application magnetic field Hs is a magnetic field which changes with time as well as the recording magnetic field Hw. That is, the main magnetic pole application magnetic field Hs also includes the recording signal Sw in the recording magnetic field Hw.

On the other hand, as illustrated in FIG. **6**C, the controlling magnetic field component Hc is generated from the controlling magnetic pole **63** based on the controlling current Ic, and is applied to the spin torque oscillator **10**.

And, as illustrated in FIG. **6**D, the modulating magnetic field component Hm is generated from the controlling magnetic pole **63** based on the controlling magnetic pole modulation current Im, and is applied to the spin torque oscillator **10**. The modulating magnetic field component Hm includes the modulation signal Sm which changes at a frequency higher than that of the recording signal Sw of the recording magnetic field Hw. For example, the frequency of the modulating magnetic field component Hm is set to be than 1.5 GHz.

As illustrated in FIG. **6**E, the external magnetic field Hext applied to the spin torque oscillator **10** is a superimposed field of the main magnetic pole application magnetic field Hs, the controlling magnetic field component Hc, and the modulating magnetic field component Hm. That is, the external magnetic field Hext is a superimposed magnetic field of the following two magnetic fields. One is the magnetic field having the frequency of the recording signal Sw included in the recording magnetic field Hw. The other is the magnetic field including the modulation signal Sm which oscillates at a frequency higher than that of the recording signal Sw of the recording magnetic field Hw.

Thus, in the magnetic recording head **51** according to the embodiment, the magnetic field including the modulation signal Sm which oscillates at a frequency higher than that of the recording signal Sw of the recording magnetic field Hw is applied. Then, the frequency fs of the high frequency magnetic field Hac generated by the spin torque oscillator **10** changes in response to the intensity (an instantaneous value of Hext) of the external magnetic field Hext. As a result, the high frequency magnetic field Hac generated by the spin torque oscillator **10** can be frequency-modulated coincident with the intensity (an instantaneous value of Hext) of the external magnetic field Hext.

FIG. **7** is a graph illustrating a characteristic of the magnetic recording head according to the first embodiment of the invention. That is, the graph illustrates a measurement of the frequency fs of the high frequency magnetic field Hac, which the spin torque oscillator **10** generates, with changing the external magnetic field Hext applied to the spin torque oscillator **10**. The horizontal and vertical axes of FIG. **7** express the external magnetic field Hext and the frequency fs, respectively. The stronger the external magnetic field Hext applied to the spin torque oscillator **10**, the higher the frequency fs of the high frequency magnetic field Hac generated by the spin torque oscillator **10**, as illustrated in FIG. **7**.

FIG. **8** is a graph schematically illustrating a characteristic of the magnetic recording head according to the first embodiment of the invention. That is, FIG. **8** is a typical graph where the polar character of the external magnetic field Hext is extended to polarity based on the experimental result illustrated in FIG. **7**. The horizontal and vertical axes of FIG. **8** express the external magnetic field Hext and the frequency fs, respectively. In a range where the absolute value of the external field Hext is larger than the coercivities of the spin injection layer **30** and the oscillation layer **10***a*, the direction of the external magnetic field Hext and the magnetization direction of the spin injection layer **30** are parallel to each other independently of the polarity of the external field Hext. For this reason, when the absolute value of the external magnetic field Hext is equal to the coercivities of the spin injection layer **30** and the oscillation layer **10***a*, the oscillation characteristic of the spin torque oscillator **10** is constant independently of the polarity of the external magnetic field Hext.

As a result, as illustrated in FIG. **8**, when the external magnetic field Hext is in the negative direction, the characteristic of the frequency fs versus the external magnetic field Hext becomes a characteristic to be acquired by folding back the characteristic illustrated in FIG. **7** where the external magnetic field Hext is in the positive direction, symmetrically with respect to the vertical axis. Therefore, when the absolute value of the external magnetic field Hext applied to the spin torque oscillator **10** becomes large irrespective of the polarity (the direction of a magnetic field) of the external magnetic field Hext, the frequency fs of the high frequency magnetic field Hac generated by the spin torque oscillator **10** becomes high. And, when the absolute value of the external magnetic field Hext becomes small, the frequency fs of the high frequency magnetic field Hac generated by the spin torque oscillator **10** becomes low.

Accordingly, the strength of the external magnetic field Hext is changed to control the frequency fs, thereby allowing it to modulate the frequency fs of the high frequency magnetic field Hac which the spin torque oscillator **10** generates.

FIGS. **9**A to **9**C are schematic views illustrating an operation of the magnetic recording head according to the first embodiment of the invention. That is, FIG. **9**A illustrates the external magnetic field Hext applied to the spin torque oscillator **10**. FIG. **9**B illustrates the change in the external magnetic field Hext by expanding the time axis (the horizontal axis). FIG. **9**C illustrates the high frequency magnetic field Hac generated by the spin torque oscillator **10**.

As illustrated in FIGS. **9**A to **9**C, when the wave height of the external magnetic field Hext is large, the frequency fs of the high frequency magnetic field Hac becomes high, and vice versa. In addition, the amplitude (the difference between the wave heights of the magnetic field Hac1 and the magnetic field Hac2) of the high frequency magnetic field Hac is constant. Thus, when the intensity of the external magnetic field Hext is modulated irrespective of the recording magnetic field Hw, the frequency fs of the high frequency magnetic field Hac generated by the spin torque oscillator **10** is modulated.

And, the magnetic recording medium **80** resonates more easily with the high frequency magnetic field Hac when the high frequency magnetic field Hac with a modulated frequency is applied to the magnetic recording medium **80** than when the high frequency magnetic field Hac with a constant frequency is applied to the magnetic recording medium **80**. That is, as illustrated in FIG. **9**C, the phases of the high frequency magnetic field Hac and the magnetization **83** of the magnetic recording medium **80** coincide well with each other just when the frequency fs of the high frequency magnetic field Hac shifts from the period T3 of a relatively higher frequency to the period T4 of a relatively lower frequency.

For example, when the frequency fs of the high frequency magnetic field Hac oscillates, the high frequency magnetic field Hac can be absorbed during two to three revolutions of the magnetization **83** of the magnetic recording medium **80** even at the time when the resonant frequency changes on the way to the reversal of the magnetization **83** of the magnetic recording medium **80**. On the other hand, when the frequency fs of the high frequency magnetic field Hac is constant, the high frequency magnetic field Hac can be absorbed during just one revolution. For this reason, when the frequency fs of the high frequency magnetic field Hac changes, the magnetic recording medium **80** resonates easily with the high frequency magnetic field Hac.

For this reason, when the high frequency magnetic field Hac is frequency-modulated, and the frequency fs thereof changes from a high frequency to a low frequency, the magnetic recording medium **80** resonates easily with the high frequency magnetic field Hac, and the energy of the high frequency magnetic field Hac can be absorbed more efficiently. As a result, a stable high frequency magnetic field assist recording is available with a relatively low frequency component of the high frequency magnetic field Hac. That is, making the magnetic recording medium **80** efficiently absorb the high frequency magnetic field Hac improves write-in capability. For this reason, even if magnetic grains included in the magnetic recording medium **80** have variations in their magnetic characteristics, it becomes possible to record on the magnetic recording medium **80**, thereby expanding an allowable range for the characteristics variations.

Thus, according to the magnetic recording head **51** of this embodiment, a magnetic recording capable of performing a stable high frequency magnetic field assist recording is provided using a lower intensity high frequency magnetic field Hac.

As illustrated in FIGS. **9**A to **9**C, the external magnetic field Hext includes a frequency component based on the recording signal Sw of the recording magnetic field Hw, i.e., a component corresponding to the period T1, and a component of frequency higher than that of the recording signal Sw, i.e., a component corresponding to the period T2 (a component of the modulation signal Sm). Then, the period T1 is set as a time interval for the magnetic recording head to perform write-in onto one recording bit of the magnetic recording medium **80**, i.e., a time interval for the magnetic recording head to pass through one recording bit.

On the other hand, the period T2 is set to be a time interval for the high frequency magnetic field Hac to be applied to each of two or more medium magnetic grains (magnetic grains) at least during a frequency-modulated period (a total period of the period T3 with a higher frequency and the period T4 with a lower modulated frequency magnetic field in the high frequency magnetic field Hac). That is, the period T2 is set to be a period for the magnetic recording head **51** to pass through one medium magnetic grain or shorter. That is, for example, when one recording bit includes N medium magnetic grains, the period T2 can be set as 1/N of the period T1.

Alternatively, the above-mentioned explains a designing guideline about the period T1 or the period T2, and these periods may be modified with variations in various constituents, manufacturing variations, etc.

FIG. **10**A is a schematic view illustrating an arrangement of the main magnetic pole **61** in the writing head portion **60** of the magnetic recording head **51** according to the first embodiment of the invention. FIG. **10**A illustrates the spin torque oscillator **10**, the controlling magnetic pole **63**, and the magnetic recording medium **80** according to the first embodiment of the invention. In FIG. **10**A, the first and second electrodes **41**, **42** are left out. FIG. **10**B is a graph illustrating a simulation of the characteristic of the magnetic recording head **51**. That is, in FIG. **10**B, the horizontal axis expresses the distance x in a direction from the main magnetic pole **61** towards the spin torque oscillator **10**, and the vertical axis expresses an effective magnetic field Heff effectively applied to the magnetic recording medium **80**. And, in the FIG. **10**B, the characteristic (the dashed line A2) of a comparative example is also illustrated in addition to the characteristic (the solid line A1) of the magnetic recording head **51** according to this embodiment.

As illustrated in FIG. **10**A, the spin torque oscillator **10** is arranged between the main magnetic pole **61** and the controlling magnetic pole **63**. And, the oscillation layer **10***a* of the spin torque oscillator **10** is arranged on the side of the main magnetic pole **61**, and the spin injection layer **30** is arranged on the side of the controlling magnetic pole **63**. In this example, the distance between the main magnetic pole **61** and the controlling magnetic pole **63** is about 60 nm. However, in the present invention, the distance between the main magnetic pole **61** and the controlling magnetic pole **63** is optional.

On the other hand, the magnetic recording medium **80** is disposed to face the medium-facing surface **61***s* of the main magnetic pole **61**. The medium-facing surface **61***s* faces the magnetic recording medium **80**. The magnetic recording medium **80** includes the medium magnetic grains **80***g* (magnetic grains) which are microscopic grains. A diameter (size) of the medium magnetic grains **80***g* is, e.g., 7 nm, and a distance between the adjacent medium magnetic grains **80***g* is, e.g., 1 nm. Therefore, the alignment pitch of the medium magnetic grains **80***g* is 8 nm.

In this example, two or three grains of the medium magnetic grains **80***g* are used as one recording bit in the moving direction of the magnetic recording head. However, the present invention is not limited to this. The size of the above-mentioned medium magnetic grains **80***g*, the distance therebetween, and the number thereof corresponding to one recording bit is optional. For example, one recording bit may include just one medium magnetic grain **80***g*.

In the medium magnetic grains **80***g*, the boundaries among the grains can be observed on the surface of the magnetic recording medium **80** using a scanning electron microscope, etc. However, the boundaries among the medium magnetic grains **80***g* are not limited to this, and may not be necessarily clear. The medium magnetic grains **80***g* may stick to each other to form grain-aggregates whose sizes allow it to control the direction of the magnetization **83**. For this reason, the medium magnetic grains **80***g* may be magnetic crystal grains included in a granular medium, for example, and may be magnetic discrete bits.

In this example, the magnetic recording head **51** moves in the direction of the arrow **85***a* relatively to the magnetic recording medium **80** to record information on the magnetic recording medium **80** by applying the recording magnetic field Hw from the main magnetic pole **61** while applying the high frequency magnetic field Hac from the spin torque oscillator **10**. Therefore, FIG. **10**A illustrates a certain instantaneous arrangement in which the magnetic recording head **51** and the magnetic recording medium **80** move relatively to each other.

As illustrated in FIG. **10**B, the effective magnetic field Heff peaks at a distance x of about 10 nm, and has a maximum of 16.2×10^3 Oe at the distance x. Then, the magnetic recording medium **80** has a coercivity Hc0 of 13.5×10^3 Oe, and the effective magnetic field Heff is much larger than the coercivity Hc0. And, in the range of the distance x from 2 nm to 15 nm, the effective magnetic field Heff is larger than the coercivity Hc0. When the medium magnetic grains **80***g* of the magnetic recording medium **80** exist in the range of the distance x, the magnetization **83** of the medium magnetic grains **80***g* is reversed in accordance with the recording signal. In the example illustrated in FIG. **10**A, the medium magnetic grain **80***h* is between the main magnetic pole **61** and the spin torque oscillator **10**, and the direction of the magnetization **83** thereof is reversed.

On the other hand, the magnetic recording head of the comparative example does not have the controlling magnetic pole modulation coil **63***b*. Therefore, the modulating magnetic field component Hm illustrated in FIG. **6**C is not applied to the spin torque oscillator **10**. Therefore, the external magnetic field Hext applied to the spin torque oscillator **10** has a waveform to be formed by removing the modulating magnetic field component Hm from the external magnetic field Hext illustrated in FIG. **6**D. That is, the wave form has only a component of the same frequency as the recording magnetic field Hw, and does not include the modulation signal Sm. In this case, since the absolute value of the external magnetic field Hext is constant, the frequency fs of the high frequency magnetic field Hac generated by the spin torque oscillator **10** is constant, and is not frequency-modulated.

Therefore, as illustrated in FIG. **10**B, in the comparative example (the dashed line A2), the maximum of the effective magnetic field Heff is 12.0×10^3 Oe, and the effective magnetic field Heff is smaller than the coercivity Hc0 at any distance x. Therefore, in the medium magnetic grains **80***g* at any distance x, the effective magnetic field Heff is smaller than the coercivity Hc0, and cannot reverse the direction of the magnetization **83**.

In the high frequency magnetic field assist recording, the high frequency magnetic field Hac is applied to the magnetic recording medium **80** so that the magnetic recording medium **80** resonates with the high frequency magnetic field Hac, thereby causing a reduction in the coercivity Hc0. Under this condition, the recording magnetic field Hw is applied to the magnetic recording medium **80** to record information thereon. FIG. **10**B illustrates the effective magnetic field Heff which changes relatively to the constant coercivity Hc0 by assuming as follows. That is, it is assumed that the coercivity Hc0 of the magnetic recording medium **80** does not change and is constant even when the magnetic recording medium **80** resonates with the high frequency magnetic field Hac. It is known that the magnetic recording medium **80** resonates with the high frequency magnetic field Hac which is frequency-modulated to reduce the high frequency magnetic field necessary for write-in by 35%.

For this reason, the magnetic recording medium **80** resonates with the high frequency magnetic field Hac so that the effective magnetic field Heff exceeds the coercivity thereof to reverse the direction of the magnetization **83**, thus allowing it to perform a magnetic recording. On the other hand, in the comparative example, the magnetic recording medium **80** does not fully resonate with the high frequency magnetic field Hac. As a result, the effective magnetic field Heff is smaller than the coercivity Hc0 at any time, and cannot reverse the direction of the magnetization **83**, thus making it impossible to perform a magnetic recording.

Thus, according to the magnetic recording head **51** of this embodiment, the high frequency magnetic field Hac is frequency-modulated to allow a stable high frequency magnetic field assist recording with the high frequency magnetic field Hac of which intensity is lower than that of the comparative example by 35%.

In addition, it is preferable to apply a combination of the higher and lower modulated frequency magnetic fields of the frequency-modulated high frequency magnetic field Hac to the respective medium magnetic grains **80***g* included in the magnetic recording medium **80**. That is, as was explained about FIG. **9**, it is preferable to apply the high frequency magnetic field Hac to two or more medium magnetic grains included in a recording bit during at least one cycle (a total period of T3 for the higher frequency and T4 for the relatively lower frequency).

Therefore, the frequency of the modulation signal Sm (signal of the modulating magnetic field component Hm in this case) which oscillates at a frequency higher than that of the recording signal Sw is preferably not less than a relative velocity between the magnetic recording head **51** and the magnetic recording medium divided by the average size of the medium magnetic grains **80***g* included in the magnetic recording medium **80**. Thereby, it is possible to apply the combination of the higher modulated frequency magnetic field and the lower modulated frequency magnetic field to each of the medium magnetic grains **80***g*. This allows each of the medium magnetic grains **80***g* to easily resonate with the high frequency magnetic field Hac, yielding a uniform write-in characteristic. This also allows it to reduce jitter in the magnetic recording and reproducing.

For example, when it is assumed as follows:

the magnetic recording medium **80** is a disk;

a peripheral velocity, i.e., a relative velocity between the magnetic recording head **51** and the magnetic recording medium **80**, is 10 m/s; and

the average size of the medium magnetic grains **80***g* of the magnetic recording medium **80** is 7 nm,

the frequency of the modulation signal Sm can be not less than 1.5 GHz.

Alternatively, the size of the medium magnetic grains **80***g* included in the magnetic recording medium **80** can particularly be a length of the medium magnetic grains **80***g* in a direction parallel to the moving direction of the magnetic recording head.

FIG. **11** is a perspective view schematically illustrating a structure of a substantial portion of another magnetic recording head according to the first embodiment of the invention. As illustrated in FIG. **11**, in another magnetic recording head **51***a* according to this embodiment, only one coil **63***c* is mounted to the controlling magnetic pole **63**. Explanations are left out because anything except this is the same as the magnetic recording head **51**.

In this case, the coil **63***c* mounted to the controlling magnetic pole **63** can be regarded as the controlling magnetic pole modulation coil **63***b* or as a coil serving as both the controlling magnetic pole modulation coil **63***b* and the controlling magnetic pole coil **63***a*. Explanations are made assuming the coil **63***c* serves as both the controlling magnetic pole coil **63***a* and the controlling magnetic pole modulation coil **63***b*.

The main magnetic pole coil **61***a* magnetizes the main magnetic pole **61** also in this case. And the coil **63***c* (the second coil) magnetizes the controlling magnetic pole **63**, and a current can be passed therethrough irrespective of the main magnetic pole coil **61***a*. That is, for example, as illustrated in FIG. **11**, the main magnetic pole coil **61***a* is connected to the recording current circuit **210**, and the coil **63***c* is connected to the current circuit **232** (the second current circuit).

The frequency modulation of the high frequency magnetic field Hac generated in the spin torque oscillator **10** is carried out by applying the external magnetic field Hext which changes at a frequency higher than that of the recording signal

Sw of the recording magnetic field Hw to be applied from the main magnetic pole **61** to the magnetic recording medium **80**.

FIGS. **12**A to **12**E are schematic views illustrating currents to be passed through another magnetic recording head according to the first embodiment of the invention, and magnetic fields to be generate by the currents. That is, FIG. **12**A illustrates the recording current Iw supplied to the recording signal Sw **61***a* at the time of recording information on the magnetic recording medium **80** by the main magnetic pole **61**, i.e., the main magnetic pole coil **61***a* of the main magnetic pole **61**, and FIG. **12**B illustrates the recording magnetic field Hw generated by the main magnetic pole **61**. As mentioned above, a portion of the magnetic field generated by the main magnetic pole **61** is the recording magnetic field Hw to be applied to the magnetic recording medium **80**, and the other portion is the main magnetic pole application magnetic field Hs to be applied to the spin torque oscillator **10**. Therefore, FIG. **12**B illustrates also the main magnetic pole application magnetic field Hs simultaneously. FIG. **12**C illustrates an controlling magnetic pole current Ic1 to be supplied to the coil **63***c*. FIG. **12**D illustrates an controlling magnetic pole magnetic field Hc1 generated by the coil **63***c*. FIG. **12**E illustrates the external magnetic field Hext to be applied to the spin torque oscillator **10**. The main magnetic pole application magnetic field Hs and the controlling magnetic pole magnetic field Hc1 are superimposed on each other to be the external magnetic field Hext.

As illustrated in FIGS. **12**A and **12**B, the recording signal Sw, i.e., a magnetic field based on the recording current Iw is generated from the main magnetic pole **61** to be applied to the magnetic recording medium **80** as the recording magnetic field Hw. The other portion of the magnetic field generated by the main magnetic pole **61** is applied to the spin torque oscillator **10** as the main magnetic pole application magnetic field Hs. As mentioned above, the main magnetic pole application magnetic field Hs is a magnetic field including the recording signal Sw included in the recording magnetic field Hw.

On the other hand, as illustrated in FIG. **12**C, the controlling magnetic pole current Ic1 is formed by superimposing the controlling current Ic on the controlling magnetic pole modulation current Im. The controlling current Ic changes in the same period as the recording signal Sw as illustrated in FIG. **5**C. The controlling magnetic pole modulation current Im includes the modulation signal Sm which oscillates at a frequency higher than that of the recording signal Sw (recording current Iw) as illustrated in FIG. **5**D. In addition, the frequency of the modulation signal Sm in the controlling magnetic pole current Ic1 is then set to be not less than 5 GHz, for example.

As illustrated in FIG. **12**D, the controlling magnetic pole field Hc1 includes the modulation signal Sm, and is applied to the spin torque oscillator **10**. The controlling magnetic pole field Hc1 is generated from the controlling magnetic pole **63** based on the controlling magnetic pole current Ic1 on which the modulation signal Sm, i.e., a high frequency component is superimposed. The modulation signal Sm oscillates at a frequency higher than that of the recording signal Sw.

As a result, as illustrated in FIG. **12**E, the external magnetic field Hext to be applied to the spin torque oscillator **10** is formed by superimposing the main magnetic pole application magnetic field Hs and the controlling magnetic pole magnetic field Hc1 on each other. The controlling magnetic pole magnetic field Hc1 includes the high frequency component (the modulation signal Sm).

Thus, also in the magnetic recording head **51***a* according to this embodiment, a magnetic field is applied to the spin torque oscillator **10**. The magnetic field includes the modulation signal Sm changing at a frequency higher than that of the recording signal Sw of the recording magnetic field Hw. This allows it to modulate the frequency fs of the high frequency magnetic field Hac generated from the spin torque oscillator **10** in response to the intensity of the external magnetic field Hext (the wave height of the external magnetic field Hext). As a result, the magnetic recording medium **80** resonates easily with the high frequency magnetic field Hac, thereby allowing it to perform a stable high frequency magnetic field assist recording with a lower intensity high frequency magnetic field Hac.

In the above explanation, it is assumed that the coil **63***c* serves as both the controlling magnetic pole coil **63***a* and the controlling magnetic pole modulation coil **63***b*. That is, it is also assumed that the current circuit **232** passes a current through the coil **63***c*. The current is supplied by superimposing the controlling magnetic pole modulation current Im including the modulation signal Sm on the controlling current Ic. However, the present invention is not limited to this. Alternatively, the coil **63***c* may serve only as the controlling magnetic pole modulation coil **63***b*. For example, the controlling magnetic pole current Ic1 supplied to the coil **63** may have the waveform of the controlling magnetic pole modulation current Im, e.g., illustrated in FIG. **5**D. Thus, the controlling magnetic pole modulation current Im including only the modulation signal Sm may be passed through the coil **63***c*. This allows it to modulate the frequency fs of the high frequency magnetic field Hac.

FIG. **13** is a perspective view schematically illustrating a structure of a substantial portion of another magnetic recording head according to the first embodiment of the invention. As illustrated in FIG. **13**, in another magnetic recording head **51***b* according to the first embodiment of the invention, an end face **63***s* on the side of the medium-facing surface **61***s* of the controlling magnetic pole **63** is recessed from the medium-facing surface **61***s* of the main magnetic pole **61**. That is, the controlling magnetic pole **63** is more recessed than the main magnetic pole **61**, viewed from the magnetic recording medium **80**. Explanations are left out because anything except this is the same as the magnetic recording head **51**.

That is, in the magnetic recording head **51***b* according to this embodiment, the end surface **63***s* of the controlling magnetic pole **63** is disposed more upward than the medium-facing surface **61***s* of the main magnetic pole **61**. The distance between the end face **63***s* on the side of the medium-facing surface **61***s* of the controlling magnetic pole **63** and the magnetic recording medium **80** is longer than the distance between the medium-facing surface **61***s* of the main magnetic pole **61** and the magnetic recording medium **80** by a distance R.

This allows it to reduce an influence of the controlling magnetic pole **63** on the magnetic recording medium **80**, thereby preventing a magnetic field generated by the controlling magnetic pole **63** from erasing information recorded on the magnetic recording medium **80**.

The controlling magnetic pole **63** reduces the influence thereof on the magnetic recording medium **80** without substantially affecting the magnetic field applied to the spin torque oscillator **10**. Thereby, the controlling magnetic pole **63** applies a suitable magnetic field to the spin torque oscillator **10** efficiently. This allows it to efficiently perform the frequency modulation of the high frequency magnetic field Hac generated in the spin torque oscillator **10**.

Thus, the magnetic recording head **51***b* of this example is configured so that the controlling magnetic pole **63** is recessed so as not to magnetically affect the magnetic recording medium **80** directly. Alternatively, the magnetic recording head **51***a* may also be configured so that the controlling magnetic pole **63** is recessed. That is, when the controlling magnetic pole **63** is provided to the magnetic recording heads according to the embodiment of the invention, the controlling magnetic pole **63** is configured so as not to magnetically affect the magnetic recording medium **80** directly.

A surface of the magnetic recording medium **80** on the side of the spin torque oscillator **10** can be arranged in a plane parallel to the medium-facing surface **61***s* of the main magnetic pole **61**. That is, the spin torque oscillator **10** is not recessed, but can be close to the magnetic recording medium **80**, unlike the controlling magnetic pole **63**. Thereby, the recording magnetic field Hw from the main magnetic pole **61** and the high frequency magnetic field Hac from the spin torque oscillator **10** can be efficiently applied to the magnetic recording medium **80** to perform an efficient magnetic recording.

As illustrated in FIG. **13**, in the portion on the side of the spin torque oscillator **10**, the shape of the controlling magnetic pole **63** can be formed so that the portion of the controlling magnetic pole **63** on the side of the spin torque oscillator **10** is close to the spin torque oscillator **10**, i.e., close to the main magnetic pole **61**, whereas the portion of the controlling magnetic pole **63** above the spin torque oscillator **10** is distant from the main magnetic pole **61**. This structure allows it to make the spin torque oscillator **10** and the controlling magnetic pole **63** close to each other, and to efficiently apply the magnetic field of the controlling magnetic pole **63** to the spin torque oscillator **10**, thereby expanding a margin of driving conditions for magnetic recording heads, and providing magnetic recording heads easy to manufacture.

FIG. **14** is a schematic view illustrating a structure of a substantial portion of another magnetic recording head according to the first embodiment of the invention. FIG. **14** is a plain view illustrating the structure of the writing head portion **60** on the side of the medium-facing surface **61***s*. FIG. **15** is a sectional view cut along the line XV-XV of FIG. **14**.

As illustrated in FIG. **14**, another magnetic recording head **51***c* according to the first embodiment of the invention is provided with side shields **64***a*, **64***b* on the sides of the main magnetic pole **61** and the spin torque oscillator **10**. That is, the main magnetic pole **61** and the spin torque oscillator **10** are arranged between the two shields **64***a*, **64***b*. The side shields **64***a*, **64***b* are arranged so as to face side walls of at least one of the main magnetic pole **61** and the spin torque oscillator **10**. The side walls are normal to the medium-facing surface **61***s* of the main magnetic pole **61**. The side shields **64***a*, **64***b* are aligned in a direction normal to the alignment direction of the main magnetic pole **61** and the spin torque oscillator **10**. Explanations are left out because anything except this is the same as the magnetic recording head **51**.

In another magnetic recording head **51***c* according to this embodiment, it is possible to control spatial spreads of the recording magnetic field Hw from the main magnetic pole **61** and the high frequency magnetic field Hac from the spin torque oscillator **10** to adjacent tracks on the magnetic recording medium **80**. Thereby, the recording magnetic field Hw from the main magnetic pole **61** and the high frequency magnetic field Hac from the spin torque oscillator **10** are superimposed on each other, and focused on a gap area between the main magnetic pole **61** and the spin torque oscillator **10**. The gap area is a recording area of the high frequency magnetic field assist recording. That is, a side-fringe magnetic field is controlled. As a result, it becomes possible to record just on a targeted track, thereby enabling a more efficient and higher density recording.

Alternatively, the side shields **64***a*, **64***b* can be integrated with the return path **62**.

It is possible to make short the distance between the side shields **64***a*, **64***b* and the main magnetic pole **61** near the medium-facing surface **61***s* of the main magnetic pole **61**, and make long the distance therebetween far from the medium-facing surface **61***s* of the main magnetic pole **61**, as illustrated in FIG. **15**. The recording magnetic field Hw of the main magnetic pole **61** can be focused more efficiently near the medium-facing surface **61***s*, thereby allowing a more effective recording. Alternatively, the side shields **64***a*, **64***b* may be provided also to the above-mentioned magnetic recording heads **51***a*, **51***b*.

Furthermore, the arrangement of the return path **62** is optional. That is, in the magnetic recording head **51** illustrated in FIG. **1**, the main magnetic pole **61** is arranged between the controlling magnetic pole **63** and the return path **62**. Alternatively, the controlling magnetic pole **63** may be arranged between the main magnetic pole **61** and the return path **62**. That is, the return path **62** can be disposed at any optional position in the respective arrangements of the main magnetic pole **61**, the controlling magnetic pole **63**, and the spin torque oscillator **10**.

Second Embodiment

FIG. **16** is a perspective view schematically illustrating a structure of a substantial portion of a magnetic recording head according to a second embodiment of the invention. As illustrated in FIG. **16**, another magnetic recording head **52** according to this embodiment is not provided with the controlling magnetic pole **63**, and the main magnetic pole modulation coil **61***b* (the modulating coil, i.e., the second coil) is mounted to the main magnetic pole **61**.

The magnetic recording head **52** is provided with a main magnetic pole **61** to apply the recording magnetic field Hw to the magnetic recording medium **80**, the spin torque oscillator **10** arranged together with the main magnetic pole **61**, the main magnetic pole coil **61***a*, and the main magnetic pole modulation coil **61***b* capable of passing a current therethrough to magnetize the main magnetic pole **61** irrespective of the main magnetic pole coil **61***a*.

That is, e.g., as illustrated in FIG. **16**, the main magnetic pole coil **61***a* is connected to a recording current circuit **210**, and the main magnetic pole modulation coil **61***b* is connected to a main magnetic pole modulation current circuit **211** (the second current circuit).

The external magnetic field Hext is applied to the spin torque oscillator **10** to modulate the frequency fs of the high frequency magnetic field Hac generated in the spin torque oscillator **10**. The external magnetic field Hext changes at a frequency higher than that of the recording signal Sw of the recording magnetic field Hw to be applied to the magnetic recording medium **80**.

Alternatively, the same materials as those for the main magnetic pole coil **61***a* or the controlling magnetic pole modulation coil **63***b* mentioned above can be employed for the main magnetic pole modulation coil **61***b*. The main magnetic pole modulation coil **61***b* can operate as well as the controlling magnetic pole modulation coil **63***b*.

FIGS. **17**A to **17**E are schematic views illustrating currents to be passed through the magnetic recording head according to the second embodiment of the invention, and magnetic fields to be generated thereby. That is, FIG. **17**A illustrates a recording current Iw to be supplied to the main magnetic pole coil **61***a* of the main magnetic pole **61**, i.e., the recording signal Sw for recording information on the magnetic recording medium **80** via the main magnetic pole **61**. FIG. **17**B illustrates a recording magnetic field component Hw1 generated by the main magnetic pole **61**. A portion of the recording magnetic field component Hw1 is applied to the magnetic recording medium **80**, and the other portion thereof is applied to the spin torque oscillator **10**. FIG. **17**C illustrates a main magnetic pole modulation current Im1 (modulating current) supplied to the main magnetic pole modulation coil **61***b*. FIG. **17**D illustrates a main magnetic pole modulating magnetic field component Hm1. FIG. **17**E illustrates the external magnetic field Hext to be applied to the spin torque oscillator **10**. A portion of the above-mentioned recording magnetic field component Hw1 and the main magnetic pole modulating magnetic field component Hm1 are superimposed on each other.

As illustrated in FIGS. **17**A and **17**B, the recording magnetic field component Hw1 based on the recording current Iw, i.e., the recording signal Sw, is generated from the main magnetic pole **61**, and a portion of the recording magnetic field component Hw1 is applied to the spin torque oscillator **10**.

On the other hand, as illustrated in FIG. **17**C, the current same as the current including the modulation signal Sm illustrated in FIG. **5**D is used for the main magnetic pole modulation current Im1. At this time, a superimposed current of the modulation signal Sm illustrated in FIG. **5**C and the controlling current Ic illustrated in FIG. **5**D may be used as the main magnetic pole modulation current Im1. The frequency of the modulation signal Sm, which oscillates at a frequency higher than the frequency of the recording signal Sw (recording current Iw), is set to be higher than 1.5 GHz.

Thereby, as illustrated in FIG. **17**D, the main magnetic pole modulating magnetic field component Hm1 changes at a frequency higher than the frequency of the recording signal Sw included in the recording magnetic field Hw to be applied to the spin torque oscillator **10**. Here, the main magnetic pole modulating magnetic field component Hm1 is generated from the main magnetic pole **61**, and based on the main magnetic pole modulation current Im1 on which the high frequency component (modulation signal Sm) is superimposed.

As illustrated in FIG. **17**E, the external magnetic field Hext applied to the spin torque oscillator **10** is formed of the above-mentioned recording magnetic field component Hw1 (a portion thereof), and the main magnetic pole modulating magnetic field component Hm1 on which the high frequency component is superimposed, thereby being formed of the following two magnetic fields:

a magnetic field with the frequency of the recording signal Sw included in the recording magnetic field Hw; and

a magnetic field including the modulation signal Sm which changes at a frequency higher than that of the recording signal Sw included in the recording magnetic field Hw.

Thus, also in the magnetic recording head **52** according to this embodiment, the magnetic field including the modulation signal Sm which changes at a frequency higher than that of the recording signal Sw of the recording magnetic field Hw is applied to the spin torque oscillator **10**. This allows it to modulate the frequency fs of the high frequency magnetic field Hac generated from the spin torque oscillator **10** in response to the intensity (wave height of Hext) of the external magnetic field Hext. As a result, the magnetic recording medium **80** resonates easily with the high frequency magnetic field Hac, thereby allowing it to perform a stable high frequency magnetic field assist recording with a lower intensity high frequency magnetic field Hac.

The main magnetic pole modulation coil **61***b* may be mounted to, for example, the magnetic recording heads **51**, **51***a* to **51***c* when the controlling magnetic pole **63** is provided. In this case, the main magnetic pole modulation coil **61***b* can be provided irrespective of the existence of the controlling magnetic pole modulation coil **63***b* of the controlling magnetic pole **63** or the coil **63***c*. When providing the controlling magnetic pole modulation coils **63***b*, **63***c* of the controlling magnetic pole **63** and the main magnetic pole modulation coil **61***b* simultaneously, it is possible to generate a highly precise modulating magnetic field using a highly precise modulation signal Sm by these coils provided, and to thus apply a highly precise external magnetic field Hext, thereby allowing a highly precise control. Alternatively, the side shields **64***a*, **64***b* may be provided to the magnetic recording head **52**.

Third Embodiment

FIG. **18** is a perspective view schematically illustrating a structure of a substantial portion of a magnetic recording head according to a third embodiment of the invention. As illustrated in FIG. **18**, another magnetic recording head **53** according to this embodiment is provided with neither the controlling magnetic pole **63** nor the main magnetic pole modulation coil **61***b* of the main magnetic pole **61**. Then, a current with a component changing at a frequency higher than that of the recording signal Sw of the recording magnetic field Hw is being passed through the main magnetic pole coil **61***a*. Here, the recording magnetic field Hw records information on the magnetic recording medium **80**.

The magnetic recording head **53** is provided with the main magnetic pole **61**, the spin torque oscillator **10**, and the main magnetic pole coil **61***a*. Here, the main magnetic pole **61** applies the recording magnetic field Hw to the magnetic recording medium **80**. The spin torque oscillator **10** is provided to the main magnetic pole **61**. The main magnetic pole coil **61***a* magnetizes the main magnetic pole **61**. The current with the modulation signal Sm changing at a frequency higher than that of the recording signal Sw of the recording magnetic field Hw is being passed through the main magnetic pole coil **61***a*.

For example, as illustrated in FIG. **18**, the main magnetic pole coil **61***a* is connected to the recording current circuit **210**. And a current including the modulation signal Sm changing at a frequency higher than that of the recording signal Sw of the recording magnetic field Hw is supplied from the recording current circuit **210** to the main magnetic pole coil **61***a*. Here, the recording magnetic field Hw records information on the magnetic recording medium **80**.

Thereby, the magnetic field (external magnetic field Hext) including the modulation signal Sm changing at a frequency higher than that of the recording signal Sw of the recording magnetic field to be applied from the main magnetic pole **61** to the magnetic recording medium **80** is applied to the spin torque oscillator **10** to modulate the frequency fs of the high frequency magnetic field Hac generated in the spin torque oscillator **10**.

FIGS. **19**A to **19**D are schematic views illustrating currents to be passed through the magnetic recording head according to the third embodiment of the invention, and magnetic fields to be generated by the currents. That is, FIG. **19**A illustrates a recording signal Sw at the time of recording information on the magnetic recording medium **80** via the main magnetic pole **61**. And FIG. **19**B illustrates a recording current Iw2 to be supplied to the main magnetic pole coil **61***a* of the main magnetic pole **61**. FIG. **19**C illustrates a recording magnetic field Hw2 generated by the main magnetic pole **61** to be applied to the magnetic recording medium **80**. FIG. **19**C illustrates also a main magnetic pole application magnetic field Hs generated by the main magnetic pole **61** to be applied to the spin torque oscillator **10**. FIG. **19**C illustrates an external magnetic field Hext to be applied to the spin torque oscillator **10**.

As illustrated in FIG. **19**A, the recording signal Sw is a signal, which changes with time, based on information to be recorded on the magnetic recording medium **80**. As illustrated in FIG. **19**B, the recording current Iw2 including the component of the recording signal Sw and the modulation signal Sm which changes at a frequency higher than that of the recording signal Sw is passed through the main magnetic pole coil **61***a*.

As illustrated in FIG. **19**C, a magnetic field is generated from the main magnetic pole **61** on the basis of the recording current Iw2, and a portion thereof is applied to the magnetic recording medium **80** as the recording magnetic field Hw2. And another portion of the magnetic field generated from the main magnetic pole **61** is applied to the spin torque oscillator **10** as the main magnetic pole application magnetic field Hs. This recording magnetic field Hw2 and the main magnetic pole application magnetic field Hs have a component of the recording signal Sw to record information, and a component of the modulation signal Sm changing at a frequency higher than that of the recording signal Sw.

Thereby, as illustrated in FIG. **19**D, the external magnetic field Hext to be applied to the spin torque oscillator **10** is the same magnetic field as the above-mentioned recording magnetic field Hw2, i.e., the main magnetic pole application field Hs. The external magnetic field Hext is also formed of the following two fields:

the magnetic field component with a frequency of the recording signal Sw included in the recording magnetic field Hw2; and

the magnetic field generated by the modulation signal Sm changing at a frequency higher than that of the recording signal Sw included in the recording magnetic field Hw2, which are superimposed on each other.

Thus, also in the magnetic recording head **53** according to this embodiment, the magnetic field including the modulation signal Sm changing at a frequency higher than that of the recording signal Sw of the recording magnetic field Hw2 is applied to the spin torque oscillator **10**. This allows it to modulate the frequency fs of the high frequency magnetic field Hac generated from the spin torque oscillator **10** in response to the intensity of the external magnetic field Hext (the wave height of the external magnetic field Hext). As a result, the magnetic recording medium **80** resonates easily with the high frequency magnetic field Hac, thereby allowing it to perform a stable high frequency magnetic field assist recording with a lower intensity high frequency magnetic field Hac. Alternatively, the magnetic recording head **53** may be provided with the side shields **64***a*, **64***b*.

FIGS. **20**A to **20**F are schematic views illustrating external magnetic fields applied to the spin torque oscillator of the magnetic recording head according to the embodiment of the invention. FIG. **20**A illustrates the recording signal Sw of the magnetic recording head. FIGS. **20**B to **20**F illustrate various kinds of modified examples of the external magnetic field Hext to be applied to the spin torque oscillator **10**.

As illustrated in FIG. **20**A, the signal component of the recording current Iw for recording information to be passed through the main magnetic pole coil **61***a* of the main magnetic pole **61** is the recording signal Sw.

As illustrated in FIG. **20**B, the external magnetic field Hext1 to be applied to the spin torque oscillator **10** has a waveform which superimposes the wave form of the recording signal Sw on that of the magnetic field (magnetic field including the modulation signal Sm) which changes in a sine wave at a frequency higher than that of the recording signal Sw. In addition, the external magnetic field Hext1 with this waveform corresponds to the above-mentioned external magnetic field Hext.

As illustrated in FIG. **20**C, the magnetic field (magnetic field including the modulation signal Sm) having a triangle waveform whose rise time and fall time are substantially equal to each other is superimposed on the external magnetic field Hext2 of the modified example. As illustrated in FIG. **20**D, the magnetic field (magnetic field including the modulation signal Sm) having a triangle waveform whose rise time and fall time are nearly zero and long, respectively, is superimposed on the external magnetic field Hext3 of another modified example. As illustrated in FIG. **20**E, the magnetic field (magnetic field including the modulation signal Sm) having a triangle waveform whose rise time and fall time are long and nearly zero, respectively, is superimposed on the external magnetic field Hext4 of another modified example. As illustrated in FIG. **20**F, the magnetic field (magnetic field including the modulation signal Sm) having a trapezoid waveform, whose rise and fall have a certain amount of time interval, with a maximum maintained for a given length of time is superimposed on the external magnetic field Hext5 of another modified example.

All of these external magnetic fields Hext1 to Hext5 include modulation signal Sm changing at a frequency higher than that of the recording signal Sw included in the recording magnetic field Hw (and the recording magnetic field Hw2) to be applied to the magnetic recording medium **80** for recording information.

This allows it to modulate the frequency of the high frequency magnetic field Hac generated from the spin torque oscillator **10** in response to the intensity of the external magnetic field Hext (the wave height of the external magnetic field Hext), and provide a magnetic recording head capable of performing a stable high frequency magnetic field assist recording using a lower intensity high frequency magnetic field Hac.

In the magnetic recording heads **52**, **53** illustrated in FIG. **16** and FIG. **18**, respectively, the spin torque oscillator **10** is arranged between the main magnetic pole **61** and the return path **62**, while the arrangement of the spin torque oscillator **10** is optional. For example, the spin torque oscillator **10** may be arranged on the opposite side of the return path **62** of the main magnetic pole **61**.

Fourth Embodiment

A magnetic recording head **54** (not shown) according to a fourth embodiment of the invention can have the same structure as the magnetic recording heads **51**, **51***a*, **51***b*, **51***c*, **52**, and **53** according to the first to third embodiments mentioned above. However, the waveform of the external magnetic field Hext applied to the spin torque oscillator **10** of the magnetic recording head **54** differs from those of the magnetic recording heads **51**, **51***a*, **51***b*, **51***c*, **52**, and **53**. An example applied to the magnetic recording head **51** provided with the controlling magnetic pole **63**, the controlling magnetic pole coil **63***a*, and the controlling magnetic pole modulation coil **63***b* is explained below.

FIGS. **21**A to **21**D are schematic views illustrating currents to be passed through the magnetic recording head according to the fourth embodiment of the invention. FIG. **21**A illustrates the recording signal Sw for recording information on the magnetic recording medium **80** via the main magnetic pole **61**. FIG. **21**B illustrates the recording current supplied to the main magnetic pole coil **61***a*. FIG. **21**C illustrates the controlling current Ic supplied to the controlling magnetic pole coil **63***a*. FIG. **21**D illustrates the controlling magnetic pole modulation current Im supplied to the controlling magnetic pole modulation coil **63***b*.

FIGS. **22**A to **22**E are schematic views illustrating magnetic fields to be generated in the magnetic recording head according to the fourth embodiment of the invention. FIG. **22**A illustrates a recording magnetic field, which is generated from the magnetic pole coil **61***a* of the magnetic pole **61**, to be applied to the magnetic recording medium **80**. FIG. **22**B illustrates a main magnetic pole application field Hs generated by the main magnetic pole coil **61***a* from the main magnetic pole **61** to be applied to the spin torque oscillator **10**. FIG. **22**C illustrates an controlling magnetic field component Hc generated from the controlling magnetic pole **63** of the controlling magnetic pole coil **63***a*. FIG. **22**D illustrates a modulating magnetic field component Hm generated from the controlling magnetic pole modulation coil **63***b* of the controlling magnetic pole **63**. FIG. **6**E illustrates the external magnetic field Hext which superimposes the respective magnetic fields mentioned above on each other to be applied to the spin torque oscillator.

As illustrated in FIGS. **21**A, **21**B and **21**C, the recording signal Sw, i.e., the recording current Iw changes based on information to be recorded on the magnetic recording medium **80**. A magnetic field is generated from the main magnetic pole **61** based on the recording signal Sw, i.e., the recording current Iw to be applied to the magnetic recording medium **80** as the recording magnetic field Hw.

Then, as illustrated in FIG. **22**B, a portion of the magnetic field generated from the main magnetic pole **61** is applied to the spin torque oscillator **10** as the main magnetic pole application magnetic field Hs. The main magnetic pole application magnetic field Hs is a magnetic field which changes with time as well as the recording magnetic field Hw. That is, the main magnetic pole application magnetic field Hs also includes the recording signal Sw.

On the other hand, as illustrated in FIG. **21**C and FIG. **22**C, the controlling magnetic field component Hc is generated from the controlling magnetic pole **63** based on the controlling current Ic, and is applied to the spin torque oscillator **10**. The controlling current Ic controls differences among recording conditions of the magnetic recording media **80** or a variation in the oscillation characteristic of the spin torque oscillator **10**.

As illustrated in FIG. **21**D, the controlling magnetic pole modulation current Im has the recording signal Sw, i.e., the same frequency as that of the recording current Iw, and the current value thereof changes in the triangle waveform pulses. That is, the controlling magnetic pole modulation current Im includes the modulation signal Sm**1** having the same frequency as the recording signal Sw. The modulation signal Sm**1** changes its absolute value in one cycle.

Thereby, as illustrated in FIG. **22**D, the modulating magnetic field component Hm is generated from the controlling magnetic pole **63**, and changes in the triangle waveform pulses to be applied to the spin torque oscillator **10**. That is, the modulating magnetic field component Hm includes the modulation signal Sm**1** having the same frequency as the recording signal Sw. The modulation signal Sm**1** changes its absolute value in one cycle.

As illustrated in FIG. **22**E, the external magnetic field Hext applied to the spin torque oscillator **10** is formed of the above-mentioned main magnetic pole application magnetic field Hs, the controlling magnetic field component Hc, and the modulating magnetic field component Hm. The external magnetic field Hext has the same frequency as that of the recording signal Sw, and the intensity thereof changes in the triangle waveform pulses. That is, the external magnetic field Hext has the same frequency as the recording signal Sw, and changes its absolute value in one cycle.

As a result, the frequency fs of the high frequency magnetic field Hac becomes high in a period T5 where the wave height of the external magnetic field Hext is relatively large, whereas the frequency fs thereof becomes low in a period T6 where the wave height thereof is relatively small.

When the intensity of the external magnetic field Hext applied to the spin torque oscillator **10** is regulated in a triangle waveform, it is possible to modulate the frequency fs of the high frequency magnetic field Hac generated by the spin torque oscillator **10**.

When using such an external magnetic field Hext, a magnetic field component thereof having a relatively larger absolute value and a magnetic field component thereof having a relatively smaller absolute value are continuously applied to the respective magnetic grains of the magnetic recording medium **80**. A total time of T5 and T6 is set to a transit time which is necessary for the magnetic recording head **51** to pass on surfaces of the respective magnetic grains of the magnetic recording medium **80**. Here, T5 is a period where the wave height of the external magnetic field Hext is relatively large, whereas T6 is a period where the wave height thereof is relatively small. In this case, the triangle waveform component of the external magnetic field Hext can have the same frequency as that of the recording signal Sw of the recording magnetic field Hw, thereby making the respective magnetic grains of the magnetic recording medium **80** correspond to recording bits for recording information on the magnetic recording medium **80**.

In addition, the absolute value of the external magnetic field Hext should just change also in this case. For example, as illustrated in FIGS. **20**B to **20**F, the absolute value of the external magnetic field Hext may have various waveforms, such as a sine waveform, a triangle waveform, a trapezoidal waveform, etc. The triangle waveform may be a triangle waveform whose rise time and fall time are substantially equal to each other, a triangle waveform whose rise time and fall time are nearly zero and long, respectively, a triangle waveform whose rise time and fall time are long and nearly zero, respectively, or a trapezoid waveform, whose rise and fall have a certain length of time, with a maximum maintained for a given length of time.

The example of the magnetic recording head **51** provided with the controlling magnetic pole **63**, the controlling magnetic pole coil **63***a*, and the controlling magnetic pole modulation coil **63***b* has been explained above. However, since the absolute value of the external magnetic field Hext applied to the spin torque oscillator **10** should just change, either one of the magnetic recording heads **51***a*, **51***b*, **51***c*, **52**, and **53** may be employed.

In the magnetic recording head **51** illustrated in FIG. **1**, the main magnetic pole **61** is arranged between the read section **70** and the spin torque oscillator **10**. Alternatively, the spin torque oscillator **10** may be arranged between the read section **70** and the main magnetic pole **61**. In the above-mentioned magnetic recording heads **51***a*, **51***b*, **51***c*, **52**, **53**, and **54**, the mutual positional relationship of the read section **70**, the main magnetic pole **61**, and spin torque oscillator **10** is optional.

Fifth Embodiment

A magnetic recording apparatus and a magnetic head assembly according to a fifth embodiment of the invention are explained below. The above-explained magnetic recording heads according to the embodiments of the invention are built into the magnetic head assembly of all-in-one write-in/read-out type, and can be mounted to the magnetic recording apparatus. In addition, the magnetic recording apparatus according to this embodiment can also have only a recording function, and can also have both recording and reproducing functions.

FIG. **23** is a perspective view schematically illustrating a configuration of the magnetic recording apparatus according to the fifth embodiment of the invention. FIGS. **24**A and **24**B are typical perspective views illustrating a configuration of a portion of the magnetic recording apparatus according to the fifth embodiment of the invention. As illustrated in FIG. **23**, a magnetic recording apparatus **150** according to the fifth embodiment of the invention is a type of apparatus using a rotary actuator. As illustrated in FIG. **23**, a recording medium disk **180** is mounted to a spindle motor **4**, and is rotated in the direction of the arrow A by the motor not shown in the figure in response to control signals from a control portion of the driving unit not shown in the figure. Alternatively, the magnetic recording apparatus **150** according to this embodiment may be provided with two or more recording medium disks **180**.

A head slider **3** which performs recording/reading information to be stored in the medium disk **180** has the configuration as was mentioned above in FIG. **2**, and is attached at a tip of a filmy suspension **154**. Here, the head slider **3** mounts the magnetic recording head according to the embodiment mentioned above, for example, near the tip thereof.

The rotation of the recording medium disk **180** results in a balance between a pressure generated by the suspension **154** and a pressure arising at the medium-facing surface (ABS) of the head slider **3**, thereby holding the medium-facing surface of the magnetic recording head apart from the surface of the recording medium disk **180** by a prescribed flying height. The magnetic recording apparatus **150** may be of so called a "contact run type" where the head slider **3** runs in contact with the recording medium disk **180**.

The suspension **154** is connected to an end of an actuator arm **155** with a bobbin portion to hold a drive coil not shown in the figure. The other end of the actuator arm **155** is provided with a voice coil motor **156**, i.e., a kind of a linear motor. The voice coil motor **156** can be configured with the drive coil (not shown) and a magnetic circuit, the drive coil being wound up onto the bobbin portion of the actuator arm **155**, the magnetic circuit including a permanent magnet arranged as facing so as to sandwich the coil, and a facing yoke.

The actuator arm **155** is held by ball bearings which are provided on upper and lower two sides of a bearing portion **157**, and can rotate slidably by the voice coil motor **156**. As a result, it is possible to move the magnetic recording head to an arbitrary position of the recording medium disk **180**.

FIG. **24**A is a perspective view illustrating a configuration of a portion of the magnetic recording apparatus according to this embodiment, and enlarges a head stack assembly **160**. FIG. **24**B is a perspective view illustrating a magnetic head stack assembly (head gimbal assembly) **158** to configure a portion of the head stack assembly **160**. As illustrated in FIG. **24**A, the head gimbal assembly **158** has an actuator arm **155** extending from the bearing portion **157** and a suspension **154** extending from the actuator arm **155**.

The head slider **3** having the magnetic recording head according to the embodiment of the invention is attached to a tip of the suspension **154**. As mentioned above, one of the magnetic recording heads according to the embodiments of the invention is attached to the head slider **3**.

That is, the magnetic head assembly (head gimbal assembly) **158** according to the embodiment of the invention is provided with one of the magnetic recording heads according to the embodiments of the invention, the head slider **3** mounting the magnetic head, the suspension **154** mounting the head slider **3** at one end thereof and the actuator arm **155** connected to the other end of the suspension **154**.

The suspension **154** has a lead for write-in/read-out of signals, a lead for a heater to adjust the flying height and a lead not shown in the figure for the oscillation of the spin torque oscillator, the leads electrically connecting to the respective electrodes of the magnetic recording head built into the head slider **3**.

The electrode pads not shown in the figure are provided in the head gimbal assembly **158**. The "electrode pads" are referred to as the "pads" simply below. For example, the head gimbal assembly **158** is provided with two pads for the coils of the main magnetic pole **61**, two pads for a magnetic reproducing element **71**, two pads for DFH (dynamic flying height), and two pads for the electrodes of the spin torque oscillator **10**. In addition, when the controlling magnetic pole coil **63***a* is provided to the head gimbal assembly **158**, the head gimbal assembly **158** is provided with two pads for the controlling magnetic pole coil **63***a*. When the controlling magnetic pole modulation coil **63***b* and the main magnetic pole modulation coil **61***b* are provided to the head gimbal assembly **158**, the head gimbal assembly **158** is provided with two pads and another two pads for the controlling magnetic pole modulation coil **63***b* and the main magnetic pole modulation coil **61***b*, respectively. Alternatively, two or more pads may be shared as a common pad in order to reduce the number thereof.

Then, a signal processor **190** not shown in the figure to write and read a signal on the magnetic recording medium using the magnetic recording head is also provided to the head gimbal assembly **158**. The signal processor **190** is mounted onto the back side of the drawing of the magnetic recording apparatus **150** illustrated in FIG. **23**, for example. Input-output lines are connected to the electrode pads of the head gimbal assembly **158**, and electrically combined with the magnetic recording head.

Thus, the magnetic recording apparatus **150** according to this embodiment is provided with the magnetic recording medium, one of the magnetic recording heads of the above-mentioned embodiments, a movable portion, a position control portion and a signal processor. The movable portion enables the magnetic recording medium and the magnetic recording head to relatively move to each other in separate or in contact while making the medium and the head face each other. The position control portion positions the magnetic recording head at a prescribed position on the magnetic recording medium. The signal processor writes and reads a signal on the magnetic recording medium.

That is, the recording medium disk **180** is used as the magnetic recording medium mentioned above. The above-mentioned movable portion can include the head slider **3**. The above-mentioned position control portion can include the head gimbal assembly **158**.

That is, the magnetic recording apparatus **150** according to this embodiment is provided with the magnetic recording medium (a magnetic recording disk **180**), the magnetic head assembly (the head gimbal assembly **158**) according to the embodiment of the invention, and the signal processor **190** writes and reads a signal on the magnetic recording medium using the magnetic recording head mounted onto the magnetic head assembly.

According to the magnetic head assembly (the head gimbal assembly **158**), using the magnetic recording head according to the embodiments mentioned above allows it to provide a magnetic head assembly capable of performing a stable high frequency magnetic field assist recording with a lower intensity high frequency magnetic field. Then, according to the magnetic recording apparatus **150** of this embodiment, using the magnetic recording head according to the embodiments mentioned above allows it to provide a magnetic recording apparatus capable of performing a stable high frequency magnetic field assist recording with a lower intensity high frequency magnetic field.

In the magnetic recording apparatus **150** according to this embodiment, the external magnetic field Hext applied to the spin torque oscillator **10** includes either a signal (the modulation signal Sm) changing at a frequency higher than that of the recording signal Sw of the recording magnetic field Hw, or a signal (the modulation signal Sm**1**) having the same frequency as the recording signal Sw to change its absolute value in one cycle. In order to apply such an external magnetic field Hext, the magnetic recording apparatus **150** is provided with various kinds of circuits being explained below.

FIG. **25** is a schematic view illustrating a configuration of a portion of another magnetic recording apparatus according to the fifth embodiment of the invention. That is, FIG. **25** illustrates the configuration of the magnetic recording apparatus employing either one of the magnetic recording heads **51**, **51***b*, and **51***c* which are provided with the controlling magnetic pole **63**, the controlling magnetic pole coil **63***a* to magnetize the controlling magnetic pole **63**, and the controlling magnetic pole modulation coil **63***b*.

As illustrated in FIG. **25**, in another magnetic recording apparatus according to the fifth embodiment, the signal processor **190** is provided with a recording current circuit **210** (a first current circuit), a magnetic pole current circuit **230** (a third current circuit), and an controlling magnetic pole modulation current circuit **231** (a modulating current circuit, i.e., a second current circuit). The recording current circuit **210** supplies the recording current Iw to the main magnetic pole coil **61***a* for recording on the magnetic recording medium **80**. Here, the recording current Iw includes the recording signal Sw for recording on the magnetic recording medium **80**. The magnetic pole current circuit **230** supplies the controlling current Ic to the controlling magnetic pole coil **63***a*. The controlling magnetic pole modulation current circuit **231** supplies the controlling magnetic pole modulation current Im to the controlling magnetic pole modulation coil **63***b*. The controlling current Ic is a current which changes coincident with a polarity reversal of the recording current Iw.

Thereby, the recording current Iw, the controlling current Ic, and the controlling magnetic pole modulation current Im illustrated in FIGS. **5**A to **5**D are supplied to generate the respective magnetic fields illustrated in FIGS. **6**A to **6**E, thereby allowing it to apply the external magnetic field Hext, e.g., illustrated in FIG. **6**E to the spin torque oscillator **10**.

Thereby, it is possible to modulate the frequency of the high frequency magnetic field Hac which the spin torque oscillator **10** generates, thus providing a magnetic recording apparatus capable of performing a stable high frequency magnetic field assist recording using a lower intensity high frequency magnetic field. Alternatively, the magnetic pole current circuit **230** (the third current circuit) may be provided if needed.

FIG. **26** is a schematic view illustrating a configuration of a portion of another magnetic recording apparatus according to the fifth embodiment of the invention. That is, FIG. **26** illustrates the configuration of the magnetic recording apparatus employing the magnetic recording head **51***a* which are provided with the controlling magnetic pole **63** having a coil **63***c*.

As illustrated in FIG. **26**, in another magnetic recording apparatus **150***b* according to this embodiment, the recording current circuit **210** and a current circuit **232** (a second current circuit). The recording current circuit **210** supplies the recording current Iw including the recording signal Sw for recording on the magnetic recording medium **80** to the main magnetic pole coil **61***a*. The current circuit **232** (the second current circuit) supplies a modulating current to the coil **63***c*.

In this example, it is assumed that the modulating current mentioned above is formed of the controlling current Ic and the controlling magnetic pole modulation current Im which are superimposed on each other. In this case, it is possible to provide an controlling current circuit **230***a* and a modulation signal current circuit **231***a* to the inside of the current circuit **232**. The controlling current circuit **230***a* supplies the controlling current Ic. The modulation signal current circuit **231***a* supplies the controlling magnetic pole modulation current Im to modulate the intensity of the external magnetic field Hext applied to the spin torque oscillator **10**.

The controlling current Ic is a current which changes coincident with a polarity reversal of the recording current Iw. Alternatively, the controlling current Ic may include retardation in phase or phase lead to some degree for the reversal polarity of the recording current Iw. On the other hand, the controlling magnetic pole modulation current Im includes either a signal (modulation signal Sm) which oscillates at a frequency higher than that of the recording signal Sw, or a signal (modulation signal Sm**1**) having the same frequency as the recording signal Sw to change its absolute value in one cycle.

Thereby, the recording current Iw and the controlling magnetic pole current Ic1, e.g., illustrated in FIGS. **12**A and **12**C, respectively, are supplied to apply the external magnetic field Hext, e.g., illustrated in FIG. **12**E to the spin torque oscillator **10**.

Thereby, according to the magnetic recording apparatus **150***b*, the frequency of the high frequency magnetic field Hac which the spin torque oscillator **10** generates can be modulated, and a magnetic recording apparatus capable of performing a stable high frequency magnetic field assist recording using a lower intensity high frequency magnetic field is provided.

Then, leaving out the controlling magnetic pole modulation coil **63***b* simplifies the configuration of the magnetic recording head, and reduces the number of interconnections of the head gimbal assembly **158**, thereby yielding a merit. Then, providing the controlling current circuit **230***a* and the modulation signal current circuit **231***a* to the inside of the current circuit **232** allows it to regulate an controlling current component (controlling current Ic) for the controlling magnetic pole **63** and a current (controlling magnetic pole modulation current Im) to modulate the external magnetic field applied to the spin torque oscillator **10**, independently of each other. Thereby, it is possible to generate unprescribed external field Hext, thus enabling a highly precise operation.

As mentioned above, the modulating current is formed of the controlling current Ic and the controlling magnetic pole modulation current Im which are superimposed on each other. However, the present invention is not limited to this. That is, for example, the modulating current may include only the component of the controlling magnetic pole modulation current Im. In this case, the current circuit **232** may be provided with only the modulation signal current circuit **231***a*.

FIG. **27** is a schematic view illustrating a configuration of another magnetic recording apparatus according to the fifth embodiment of the invention. That is, FIG. **27** illustrates the configuration of the magnetic recording apparatus employing either one of the magnetic recording heads **51**, **51***b*, and **51***c* which have the controlling magnetic pole **63**, the controlling magnetic pole coil **63***a* to magnetize the controlling magnetic pole **63**, and the controlling magnetic pole modulation coil **63***b*.

As illustrated in FIG. **27**, in another magnetic recording apparatus **150***c* according to the embodiment, the signal processor **190** of the magnetic recording apparatus **150***a*, illustrated in FIG. **25**, further includes a recording signal circuit **240** connected to the recording current circuit **210**, the controlling magnetic pole current circuit **230**, and the controlling magnetic pole modulation current circuit **231**. The recording signal circuit **240**, thus configuring the signal processor **190** of the magnetic recording apparatus **150***c*.

The recording signal circuit **240** supplies the recording signal Sw, e.g., shown FIG. **5**A to the recording current circuit **210**. Thereby, the recording current circuit **210** generates the recording current Iw to supply to the main magnetic pole coil **61***a*. In FIG. **5**A, the recording signal Sw and the recording current Iw are illustrated as identical currents. However, the recording signal Sw is for recording information, and the recording current Iw is passed through the main magnetic pole coil **61***a* based on the recording signal Sw. The recording current Iw may show a polarity opposite to that of the recording signal Sw depending on the winding manner of the main magnetic pole coil **61***a* of the main magnetic pole **61** in some cases.

The controlling magnetic pole current circuit **230** generates the controlling current Ic based on the recording signal Sw. And the controlling magnetic pole modulation current circuit **231** generates the controlling magnetic pole modulation current Im on the timing of the recording signal Sw.

Thus, providing the recording signal circuit **240** allows the signal processor **190** to operate efficiently and stably.

Alternatively, the recording signal circuit **240** may be connected to the recording current circuit **210** and the controlling magnetic pole current circuit **230** which is not connected to the controlling magnetic pole modulation current circuit **231**. The controlling magnetic pole modulation current circuit **231** may generate the controlling magnetic pole modulation current Im independently of the recording signal Sw.

Alternatively, the recording signal circuit **240** may be provided to the magnetic recording apparatus **150***b* having the controlling magnetic pole **63**, the controlling magnetic pole coil **63***a*, and the coil **63***c*, but not the controlling magnetic pole modulation coil **63***b*. Then, the recording signal circuit **240** is connected to both the recording current circuit **210** and the current circuit **232**. That is, the recording signal circuit **240** is connected to at least one of the controlling current circuit **230***a* and the modulation signal current circuits **231***a* which are provided to the current circuit **232**, thereby allowing it to generate the controlling current Ic and the controlling magnetic pole modulation current Im based on the output of the recording signal circuit **240**, respectively.

FIG. **28** is a schematic view illustrating a configuration of another magnetic recording apparatus according to the fifth embodiment of the invention. As illustrated in FIG. **28**, another magnetic recording apparatus **150***d* according to this embodiment corresponds to the magnetic recording apparatus **150***c* illustrated in FIG. **27** in which the signal processor **190** further includes a phase regulation circuit **250**.

The electric signal (recording signal Sw) from the recording signal circuit **240** is input to the phase regulation circuit **250**. And, the phase regulation circuit **250** supplies a phase-regulated electric signal whose phase has already been regulated to at least one of the recording current circuit **210**, the controlling magnetic pole current circuit **230**, and the controlling magnetic pole modulation current circuit **231**.

The example of the magnetic recording apparatus **150***d* illustrated in FIG. **28** includes the phase regulation circuit **250***a* (**250**). The electric signal (recording signal Sw) from the recording signal circuit **240** is input to the phase regulation circuit **250***a*. The phase regulation circuit **250***a* supplies the phase-regulated electric signal whose phase has already been regulated to the controlling magnetic pole current circuit **230**.

That is, the signal processor **190** further includes the phase regulation circuit **250***a* to advance or delay the current (the controlling current Ic in this case) supplied to the controlling magnetic pole coil **63***a* more than the polarity reversal of the recording current Iw by a prescribed time.

That is, the phase regulation circuit **250***a* is arranged between the recording signal circuit **240** and the controlling magnetic pole current circuit **230**. And, the phase regulation circuit **250***a* can serve as a phase pre-compensation circuit or a delay circuit, for example. Thereby, the controlling current Ic is more advanced or delayed than the polarity reversal of the recording signal Sw by a prescribed time.

In addition, the phase regulation circuit **250** may be provided to, e.g., the magnetic recording head **51***a* with the coil **63***c* mounted to the controlling magnetic pole **63** as only one coil. In this case, the phase regulation circuit **250** is provided between the recording signal circuit **240** and the current circuit **232**. That is, the phase regulation circuit **250** can be disposed between the recording signal circuit **240** and the current circuit **230***a*, or between the recording signal circuit **240** and the modulation signal current circuit **231***a*. Also in this case, the phase regulation circuit **250** may be disposed between the recording signal circuit **240** and the recording current circuit **210**.

FIGS. **29**A to **29**C are schematic views illustrating operation currents for another magnetic recording apparatus according to the fifth embodiment of the invention. FIG. **29**A illustrates the electric signal to be output from the magnetic recording apparatus **150***d* according to this embodiment, i.e., the recording signal Sw. FIG. **29**B illustrates the recording current to be passed through the main magnetic pole coil **61***a*. FIG. **29**C illustrates the controlling current Ic to be passed through the controlling magnetic pole coil **63***a*. In FIGS. **29**A to **29**C, the horizontal axis expresses time t. The vertical axes of FIGS. **29**A, **29**B, and **29**C express the recording signal Sw, the recording current Iw, and the controlling current Ic, respectively.

As illustrated in FIGS. **29**A and **29**B, the recording current Iw changes coincident with the recording signal Sw, and has the same phase and the same polarity as the recording signal Sw in the magnetic recording apparatus **150***d* according to this embodiment. On the other hand, the phase of the controlling current Ic can be more advanced or delayed than that of the recording signal Sw by a predetermined phase, i.e., a predetermined time Δt.

For example, when changing the controlling current Ic coincident with the polarity reversal of the recording current Iw (i.e., when Δt is 0), a time which the oscillation frequency of the spin torque oscillator **10** takes to reach a steady value is longer than a time which the recording current Iw takes to reverse its polarity in some cases. In such cases, it is effective to delay the phase of the controlling current Ic more than that of the recording current Iw by just a predetermined time Δt. That is, in a period of Δt which has passed since a polarity reversal of the recording current Iw took place, a magnetic field applied from the controlling magnetic pole **63** to the spin torque oscillator **10** and a magnetic field applied from the main magnetic pole **61** to the spin torque oscillator **10** tends to intensify mutually. Thereby, the oscillation condition of the spin torque oscillator **10** reverses more rapidly. As a result, a magnetic recording apparatus capable of performing a stable and quality high frequency magnetic field assist recording is provided.

Thus, according to another magnetic recording apparatus **150***d* of this embodiment, it is possible to provide a magnetic recording apparatus capable of performing a stable and efficient high frequency magnetic field assist recording which is based on a rapid reversal of the oscillation condition of the spin torque oscillator **10**, and a stability of the uniform oscillation frequency of the spin torque oscillator **10**.

In this example, the phase regulation circuit **250***b* (not shown) may be provided between the recording signal circuit **240** and the controlling magnetic pole modulation current circuit **231** as the phase regulation circuit **250**. That is, the electric signal (recording signal Sw) from the recording signal circuit **240** is input to the phase regulation circuit **250***b*. The phase regulation circuit **250***b* supplies a phase-regulated electric signal whose phase has already been regulated to the controlling magnetic pole modulation current circuit **231**. Thereby, the phase of the controlling magnetic pole modulation current Im can be more advanced or delayed than that of the recording signal Sw by a predetermined phase. The phase regulation circuit **250***b* advances or delays the polarity reversal of the controlling magnetic pole modulation current Im more than that of the recording signal Sw by a prescribed time.

Alternatively, the above-mentioned phase regulation circuits **250***a*, **250***b* may be provided simultaneously. Then, the respective phase shifts according to the phase regulation circuits **250***a*, **250***b* can be controlled independently. Thereby, the external magnetic field Hext can be controlled more precisely.

FIG. **30** is a schematic view illustrating a configuration of another magnetic recording apparatus according to the fifth embodiment of the invention. As illustrated in FIG. **30**, in another magnetic recording apparatus **150***e* according to the fifth embodiment of the invention, a phase regulation circuit **250***c* is provided between the recording signal circuit **240** and the recording current circuit **210**.

The phase regulation circuit **250***b* advances or delays the polarity reversal of the recording current Iw more than that of the recording signal Sw by a prescribed time. Thereby, the phase of the recording current Iw is more advanced or delayed than that of the controlling current Ic by a prescribed time.

Also in this case, it is possible to provide a magnetic recording apparatus capable of performing a stable and efficient high frequency magnetic field assist recording which is based on a rapid reversal of the oscillation condition of the spin torque oscillator, and a stability of the uniform oscillation frequency of the spin torque oscillator **10**.

Also in this case, the phase regulation circuit **250***a* may be provided between the recording signal circuit **240** and the controlling magnetic pole current circuit **230**, or the phase regulation circuit **250***b* (not shown) may be provided between the recording signal circuit **240** and the controlling magnetic pole modulation current circuit **231** as a phase regulation circuit **250**.

Thus, the phase regulation circuit **250** (for example, the phase regulation circuits **250***a* to **250***c*) provided to the signal processor **190** should just make currents such as the controlling currents, the controlling magnetic pole current Ic1, the controlling magnetic pole modulation current Im more advanced or delayed than the polarity reversal of the recording current Iw by a predetermined time. The phase regulation circuit **250** is provided at least at one of the positions which are between the recording signal circuit **240** and the recording current circuit **210**, between the recording signal circuit **240** and the current circuit **232**, between the recording signal circuit **240** and the controlling current circuit **230***a*, between the recording signal circuit **240** and the controlling magnetic pole modulation current circuits **231**, and between the recording signal circuit **240** and the modulation signal current circuits **231***a*. Alternatively, the phase regulation circuit **250** may be housed in at least either one of the recording signal circuit **240**, the recording current circuit **210**, the controlling magnetic pole current circuit **230**, the current circuit **232**, the controlling current circuit **230***a*, the controlling magnetic pole modulation current circuit **231**, and the modulation signal current circuit **231***a*.

FIG. **31** is a schematic view illustrating a partial configuration of another magnetic recording apparatuses according to the fifth embodiment of the invention. That is, FIG. **31** illustrates the configuration of the magnetic recording apparatus employing the magnetic recording head **52** illustrated in FIG. **16**, which is not provided with the controlling magnetic pole **63** as a magnetic recording head, but provided with the main magnetic pole coil **61***a* and the main magnetic pole modulation coil **61***b* mounted to the main magnetic pole **61**.

As illustrated in FIG. **31**, the magnetic recording apparatus **150***f* according to this embodiment is provided with the magnetic recording medium **80**, the magnetic head assembly (not shown), and the signal processor **190**. The signal processor **190** performs write-in on the magnetic recording medium **80** and read-out therefrom with a magnetic recording head included in the magnetic head assembly.

In the example of the magnetic recording apparatus **150***f*, the magnetic recording head **52**, e.g., illustrated in FIG. **16** is employed, and provided with the followings:

- the main magnetic pole **61** to apply the recording magnetic field Hw to the magnetic recording medium **80**;
- the spin torque oscillator **10** arranged in the proximity of the main magnetic pole **61**;
- the main magnetic pole coil **61***a* to magnetize the main magnetic pole **61**; and
- the main magnetic pole modulation coil **61***b* (the modulating coil, i.e., the second coil) to magnetize the main magnetic pole **61**, through which a current can be passed.

In addition, the magnetic head assembly is provided with the followings: the above-mentioned magnetic recording head;

- the head slider carrying the magnetic recording head;
- the suspension mounting the head slider on one end thereof; and
- the actuator arm connected to the other end of the suspension.

The signal processor **190** is provided with the followings:

- the recording current circuit **210** to supply the recording current Iw including the recording signal Sw to the main magnetic pole coil **61***a* for recording on the magnetic recording medium **80**; and
- the main magnetic pole modulation current circuit **211** (the controlling current circuit).

Thereby, the recording current Iw and the main magnetic pole modulation current Im1 illustrated in FIGS. **17**A and **17**C are supplied to apply the external magnetic field Hext illustrated in FIG. **17**E and FIG. **22**E.

Thereby, it is possible to modulate the frequency of the high frequency magnetic field Hac which the spin torque oscillator **10** generates, thus providing a magnetic recording apparatus capable of performing a stable high frequency magnetic field assist recording using a lower intensity high frequency magnetic field.

Then, leaving out the controlling magnetic pole **63** and the coils to magnetize the pole **63** simplifies the configuration of the magnetic recording head, and reduces the number of interconnections of the head gimbal assembly **158**, thereby yielding a merit. Then, providing the recording current circuit **210** and the main magnetic pole modulation current circuit **211** additionally allows it to regulate recording current Iw and the main magnetic pole modulation current Im1 to modulate the external magnetic field Hext applied to the spin torque oscillator **10**, independently of each other. Thereby, it is possible to generate unprescribed external field Hext, thus allowing a highly precise operation.

The recording signal circuit **240** connected to the recording current circuit **210** may be further provided to the signal processor **190**. Thereby, the recording current circuit **210** generates the recording current Iw based on the recording signal Sw supplied from the recording signal circuit **240**, and supplies it to the main magnetic pole coil **61***a*.

Alternatively, the recording signal circuit **240** may be connected to the main magnetic pole modulation current circuit **211**. Thereby, the main magnetic pole modulation current circuit **211** generates the main magnetic pole modulation current Im1 based on the recording signal Sw supplied from the recording signal circuit **240**, and supplies the current Im1 to the main magnetic pole modulation coil **61***b*.

Also in this case, the phase regulation circuit **250** may be further provided at least at one of the positions which are between the recording current circuit **210** and the recording signal circuit **240**, and between the main magnetic pole modulation current circuit **211** and the recording signal circuit **240**, thereby allowing it to adjust the phases of the currents generated by these circuits.

FIG. **32** is a schematic view illustrating a configuration of another magnetic recording apparatus according to the fifth embodiment of the invention. As illustrated in FIG. **32**, the magnetic recording apparatus **150***g* according to the fifth embodiment of the invention employs the magnetic recording head **53** illustrated in FIG. **18**, which is not provided with the controlling magnetic pole **63** as a magnetic recording head, but provided with the main magnetic pole coil **61***a* but not with the main magnetic pole modulation coil **61***b* mounted to the main magnetic pole **61**.

That is, the magnetic recording apparatus **150***g* is provided with the followings:

the magnetic recording medium **80**;
the magnetic recording head **53**;
the recording current circuit **210**; and
the signal processor **190**.

The magnetic recording head **53** is provided with the followings:

the main magnetic pole **61** to apply the recording magnetic field Hw to the magnetic recording medium **80**;
the spin torque oscillator **10** arranged in the proximity of the main magnetic pole **61**; and
the main magnetic pole coil **61***a* to magnetize the main magnetic pole **61**.

The recording current circuit **210** supplies the recording current Iw including the recording signal Sw to the main magnetic pole coil **61***a* for recording on the magnetic recording medium **80**. The signal processor **190** performs write-in on the magnetic recording medium **80** and read-out therefrom with the magnetic recording head **53**.

Then, the recording current Iw2 includes either one of the following two signals. One is the modulation signal Sm changing at a frequency higher than that of the recording signal Sw of the recording magnetic field Hw. The other is the modulation signal Sm**1** having the same frequency as the recording signal Sw, and changing its absolute value in one cycle.

That is, the recording current circuit **210** supplies the recording current Iw2 illustrated in FIG. **19**B to the main magnetic pole coil **61***a*, for example. The recording current circuit **210** supplies the recording current Iw2 to the main magnetic pole coil **61***a*. The recording current Iw2 superimposes the modulating current Im illustrated in FIG. **21**D on the recording current Iw illustrated in FIG. **21**B.

That is, in this example, the recording current circuit **210** has the recording signal current circuit **210***a* and the modulation signal current circuit **211***a*. The recording signal current circuit **210***a* supplies the recording signal current Iw1 including the recording signal Sw. The modulation signal current circuit **211***a* supplies either one of the following two modulation signals. One is the signal (the modulation signal Sm) changing at a frequency higher than that of the recording signal Sw. The other is the signal (the modulation signal Sm**1**) having the same frequency as the recording signal Sw, and changing its absolute value in one cycle.

Thereby, the recording current Iw2 formed of the recording signal current Iw1 including the recording signal Sw and the main magnetic pole modulation signal current Im2 is supplied to the main magnetic pole coil **61***a* to apply the external magnetic field Hext, illustrated in FIGS. **19**D and **22**E, to the spin torque oscillator **10**.

Thereby, according to the magnetic recording apparatus **150***g*, the frequency modulation of the high frequency magnetic field Hac which spin torque oscillator **10** generates can be performed, and a magnetic recording apparatus capable of a stable high frequency magnetic field assist recording with a lower intensity high frequency magnetic field Hac.

Also in this case, the recording signal circuit **240** can be provided. The recording signal current circuit **210***a* generates the recording signal current Iw1 based on the output of the recording signal circuit **240**. The modulation signal current circuit **211***a* generates the main magnetic pole modulation signal current Im2 based on the output of the recording signal circuit **240**. Alternatively, the phase regulation circuit **250** may be further provided at least at one of the positions which are between the recording current circuit **210** and the recording signal circuit **240**, and between the main controlling magnetic pole modulation current circuit **211***a* and the recording signal circuit **240**, thereby allowing it to adjust the phases of the currents generated by these circuits.

In any one of the magnetic recording apparatuses **150**, **150***a* to **150***g* according to the embodiments of the invention, the spin torque oscillator **10** can be arranged on the reading side of the main magnetic pole **61**. In this case, the magnetic recording layer **81** of the magnetic recording medium **80** firstly faces the spin torque oscillator **10**, and secondly faces the main magnetic pole **61**. That is, when the magnetic recording head of the magnetic recording apparatus has a reading portion **70**, the spin torque oscillator **10** can be arranged on the reading side of the reading portion **70** of the main magnetic pole **61**.

In any one of the magnetic recording apparatuses **150**, **150***a* to **150***g* according to the embodiments of the invention, the spin torque oscillator **10** can arranged on the trailing side of the main magnetic pole **61**. In this case, the magnetic recording layer **81** of the magnetic recording medium **80** firstly faces the main magnetic pole **61**, and secondly faces the spin torque oscillator **10**. That is, when the magnetic recording head of the magnetic recording apparatus has a reading portion **70**, the spin torque oscillator **10** can be arranged on the reverse side of the reading portion **70** of the main magnetic pole **61**.

The magnetic recording medium which can be used for the magnetic recording apparatuses of the embodiments mentioned above is explained below. FIGS. **33**A and **33**B are typical perspective views illustrating configurations of the magnetic recording medium of a magnetic recording apparatus according to the embodiment of the invention. As illustrated in FIGS. **33**A and **33**B, the magnetic recording medium **80** used for the magnetic recording apparatus according to the embodiment of the invention has magnetic discrete tracks (recording tracks) **86** including magnetic grains which are separated from each other by a nonmagnetic material (or air) **87** and have magnetization perpendicularly oriented to the medium surface. When this magnetic recording medium **80** is rotated by the spindle motor **4** and moves in the medium moving direction **85**, one of the magnetic recording heads according to the embodiments mentioned above is arranged in a prescribed position to thereby form recorded regions of magnetization **84**. Thus, the magnetic recording medium **80** may be a discrete track medium where the adjacent recording tracks were formed to be separated by the nonmagnetic portions in the magnetic recording medium according to the embodiment of the invention.

The width (TS) of the recording portion facing the recording tracks **86** of the spin torque oscillator **10** is set to the width (TW) of the tracks **86** or larger and the recording track pitch or narrower. This setting allows it to suppress a reduction in the coercivity of the adjacent recording tracks due to a high frequency magnetic stray field from the spin torque oscillator **10**. For this reason, in magnetic recording medium **80** of this example, the high frequency magnetic field assist recording can be focused just on a correct track which should be recorded.

According to this example, it is easier to use the high frequency assist recording apparatus for a narrow track rather than to use a perpendicular magnetic recording medium formed of an unprocessed continuous film. According to a conventional magnetic recording method, it was impossible to use FePt, SmCo, etc. as magnetic fine grains, because the magnetic fine grains of FePt, SmCo, etc. with extremely high magnetic anisotropy energy (Ku) were too difficult to switch the magnetization direction thereof, i.e., to write in. However, according to the high frequency assist recording method, it is possible to employ the magnetic fine grains of FePt, SmCo, etc. which are reduced even to a nanometer size, and to provide a magnetic recording apparatus capable of attaining a linear recording density much higher than that of the conventional magnetic recording method. The magnetic recording apparatus according to this embodiment can firmly record even on the discrete type magnetic recording medium **80** with a high coercivity, thereby allowing it to attain a high-density and rapid recording.

FIGS. **34**A and **34**B are typical perspective views illustrating configurations of another magnetic recording medium of the magnetic recording apparatus according to the embodiment of the invention. As illustrated in FIGS. **34**A and **34**B, another magnetic recording medium **80** which can be employed for the magnetic recording apparatus according to the embodiment of the invention has magnetic discrete bits **88** mutually separated by the nonmagnetic material **87**. When this magnetic recording medium **80** is rotated by the spindle motor **4** and moves in the medium moving direction **85**, the magnetic recording head according to the embodiment of the invention is arranged in a prescribed position to thereby form recorded magnetization **84**. Thus, the magnetic recording medium **80** may be a discrete bit medium of which recording magnetic dots are separated by the nonmagnetic portions to be regularly arranged in the magnetic recording medium according to the embodiment of the invention.

The magnetic recording apparatus according to this embodiment can firmly record even on the discrete type magnetic recording medium **80** with a high coercivity, allowing it to attain a high-density and rapid recording.

The width (TS) of the recording portion facing the recording tracks **86** of the spin torque oscillator **10** is set to the width (TW) of the tracks **86** or larger and the recording track pitch or narrower. This setting allows it to suppress a reduction in the coercivity of the adjacent recording tracks due to a high frequency magnetic stray field from the spin torque oscillator **10**. For this reason, in magnetic recording medium **80** of this example, the high frequency magnetic field assist recording can be focused just on the track which should be recorded. According to this example, enhancing the anisotropy energy (Ku) and the miniaturizing the magnetic discrete bits **88** possibly lead to a high frequency magnetic field assist recording apparatus capable of attaining a high recording density of 10 $Tbits/inch^2$ or more, as long as the heat fluctuation tolerance of the bits **88** is maintained under the environment of usage thereof.

Sixth Embodiment

FIG. **35** is a flow chart illustrating a magnetic recording method according to a sixth embodiment of the invention. The magnetic recording method according to this embodiment records information on the magnetic recording medium **80** using the main magnetic pole **61** to apply the recording magnetic field Hw (a first magnetic field) to the magnetic recording medium **80**, and the spin torque oscillator **10** arranged near the main magnetic pole **61**.

As illustrated in FIG. **35**, in the magnetic recording method according to this embodiment, the recording magnetic field Hw is applied to the magnetic recording medium **80** while applying a magnetic field (the external magnetic field Hext, a second magnetic field), which includes a signal (the modulation signal Sm) changing at a frequency higher than that of the recording signal Sw, to the spin torque oscillator **10** (STEP S**110**).

At this time, Hext, Hext1 to Hext5 are used as the external magnetic field Hext including the modulation signal Sm as was explained with respect to FIG. **6**E, FIG. **12**E, FIG. **17**E, FIG. **19**D, and FIGS. **20**B to **20**F.

The recording magnetic field Hw (the first magnetic field) is applied to the magnetic recording medium **80** while applying a magnetic field (the external magnetic field Hext, the second magnetic field), which includes a signal (the modulation signal Sm**1**) having the same frequency as the recording signal Sw and changing its absolute value in one cycle, to the spin torque oscillator **10** (STEP S**210**).

At this time, the external magnetic field Hext including the modulation signal Sm**1** as was explained with respect to FIG. **22**E is used.

Using the magneto-resistive effect element recording method according to this embodiment allows it to modulate the frequency of the high frequency magnetic field Hac generated in the spin torque oscillator **10**, and perform a stable high frequency magnetic field assist recording with a lower intensity high frequency magnetic field.

The embodiments of the invention have been explained with reference to the examples. However, the present invention is not limited to these examples. For example, when those skilled in the art appropriately select to combine two or more of the configurations of the spin torque oscillator, the magnetic recording head, the magnetic head assembly, and the magnetic recording apparatus from a known range, and the same effect as described above can be obtained, they are also incorporated in the present invention. What combined technically any two or more elements of the respective examples to the extent possible is included in the scope of the present invention as long as including the gist of the present invention.

When those skilled in the art appropriately change or modify the designs of the spin torque oscillator, the magnetic recording head, the magnetic head assembly, and the magnetic recording apparatus to practice all the changed or modified ones, and the same effect as described above can be obtained, they are also incorporated in the present invention.

In addition, those skilled in the art can change or modify the embodiments according to the invention. Then the changed or modified examples can be understood to be incorporated in the scope of the present invention.

What is claimed is:

1. A magnetic recording apparatus, comprising:
a magnetic recording medium;
a magnetic recording head including:
a first magnetic pole to apply a recording magnetic field to the magnetic recording medium;
a second magnetic pole provided parallel to the first magnetic pole;
a spin torque oscillator at least a portion of which is provided between the first magnetic pole and the second magnetic pole;
a first coil to magnetize the first magnetic pole; and
a second coil through which a current is passed independently of the first coil; and

a signal processor to write and read a signal on the magnetic recording medium by using the magnetic recording head, the signal processor including:
a first current circuit to supply a recording current to the first coil, the recording current including a recording signal to be recorded on the magnetic recording medium; and
a second current circuit to supply a modulating current to the second coil, wherein
the modulating current includes either one of a signal changing at a frequency higher than that of the recording signal and a signal having the same frequency as the recording signal and changing an absolute value thereof in one cycle.

2. The apparatus according to claim **1**, wherein
the second current circuit includes a modulation signal current circuit and a controlling current circuit;
the modulation signal current circuit supplies a current including either one of a signal changing at a frequency higher than that of the recording signal and a signal having the same frequency as the recording signal and changing an absolute value thereof in one cycle; and
the controlling current circuit supplies a controlling current changing coincident with a polarity reversal of the recording current.

3. The apparatus according to claim **1**, wherein
the signal processor further includes a recording signal circuit to supply an electric signal to the first current circuit;
the electric signal includes a signal to be recorded on the magnetic recording medium; and
the second current circuit supplies the controlling current based on the electric signal.

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